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STRUCTURE AND STRATIGRAPHY OF CAMPBELL FLATS ANTICLINORIUM NEAR GRANDE CACHE, ALBERTA

by

C. BRUCE WRIGHTSON

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled Structure and Stratigraphy of Campbell Flats Anticlinorium near Grande Cache, Alberta ....

submitted by Charles B. Wrightson ....

in partial fulfilment of the requirements for the degree of Master of Science

ABSTRACT

The Campbell Flats anticlinorium, in the hanging wall of the Mason thrust, underlies Mount Hamell and Grande Mountain, and crosses the Smoky River some 15 km north-northwest of the town of Grande Cache. An area of about 60 sq km was mapped in detail, field data being stored, retrieved and processed using the computer. Existing computer-based procedures were used for example to plot maps, prepare orientation diagrams, divide the area into 22 domains within which folding can be considered cylindrical, calculate fold-axes, rotate domains, prepare cross-sections by downplunge projection, and calculate stratigraphic thicknesses.

A computer-based method was developed to prepare structure-contour maps of coal seams or other stratigraphic horizons using only orientational, stratigraphic and positional outcrop data.

It has four steps: (a) establishment of domains within which the horizon is approximately cylindrically folded; (b) construction of the horizon profile in each domain; (c) projection of each profile parallel to its fold-axis in order to generate the coordinates of a set of points on the horizon in each domain; (d) computer-contouring of the resulting elevations. The first and fourth steps use known procedures. The second step can be carried out graphically using a computer plot that shows the geographic location,

stratigraphic position and bedding trace of each outcrop projected onto a plane normal to the fold-axis. Alternatively, where the stratigraphic positions of the outcrops are known precisely enough and the structure is not too complex, the computer can be instructed to interpolate the horizon between the various projected outcrops. The third step involves using the appropriate digitized profile and fold-axis to predict the horizon's depth beneath each outcrop and saving these values for the contouring stage. In the case of coal seams, overburden thickness maps can also be prepared using this method.

The Campbell Flats anticlinorium exposes strata ranging from the Upper Jurassic - Lower Cretaceous Nikanassin Formation to the Upper Cretaceous Kaskapau Formation. The coal-bearing Luscar Formation was examined in detail and found to consist of four units: (A) 90 m of interbedded sandstone, siltstone and shale with several thin coal seams, the most important being 1.5 m thick; (B) 30 m of marine shale, equivalent to the Moosebar Formation of northeastern British Columbia; (C) 270 m of interbedded sandstone, siltstone and shale with three mineable seams totalling 8 m in thickness; (D) 170 m of sandstone with some interbedded shale and conglomerate.

From the structural standpoint, folds within the Campbell Flats anticlinorium are characterized by planar limbs, narrow hinge zones and some intralimb faults. The orientations of the fold-axes and axial planes of the folds

change rapidly from one area to another. These geometric characteristics and the association with considerable bedding-plane slip suggest that the dominant folding mechanism was kinking rather than buckling.

ACKNOWLEDGEMENTS

The author would like to extend his utmost appreciation to Dr. Henry Charlesworth who provided supervision, encouragement and criticism throughout the duration of this study. Dr. Chris Gold's assistance and suggestions were much appreciated during the development of the structure contouring procedure. Discussions with Dr. C.R. Stelck on the stratigraphy and paleontology of the Cretaceous strata in the Rocky Mountain Foothills proved invaluable. Useful discussions about data manipulation and processing were had with Mr. W.E. Kilby. The author would also like to acknowledge the help given by Dr. E.A. Babcock of the Alberta Research Council, Mr. J.J. Crowhurst and Mr. P.L. Wright of McIntyre Mines, and field assistant Mr. Hans Wain.

McIntyre Mines, as well as making available the detailed topographic maps, borehole data and technical reports in their possession, provided considerable financial assistance in the form of a field assistant, transportation and living expenses. The Alberta Research Council paid the author's salary while he was in the field. Further financial assistance was provided by (1) the National Research Council in the form of a postgraduate scholarship to the author and a grant to Dr. Charlesworth, (2) the Geological Survey of Canada in the form of a grant to Dr. Charlesworth, and (3) the University of Alberta in the form of a partial graduate

teaching assistantship.

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INTRODUCTION

Abundant reserves of high quality metallurgical coal are present in the Lower Cretaceous Luscar Formation of the Rocky Mountain Foothills in west-central Alberta. This coal has been mined since the beginning of the century and will undoubtedly be exploited for many years to come. Exploration and mapping for coal in the Smoky River region began early in the 1900's but because of poor markets and the remoteness of the area activity was suspended until recent times.

This thesis describes the detailed structure and stratigraphy of the Luscar Formation, about which little is known, in a small area straddling the Smoky River near Grande Cache (Fig. 1). The aims of the thesis were essentially four-fold: (1) to determine the stratigraphy of the Luscar Formation, in particular the number and distribution of coal seams; (2) to describe and analyse the structure of the Luscar and adjacent formations; (3) to develop a numerical, computer-based method for preparing structure contour and overburden thickness maps; and (4) to demonstrate the usefulness of this and other numerical, computer-based methods in determining, displaying and analysing the detailed structure of coal measures. Field work for this study was carried out in 1977 during the four

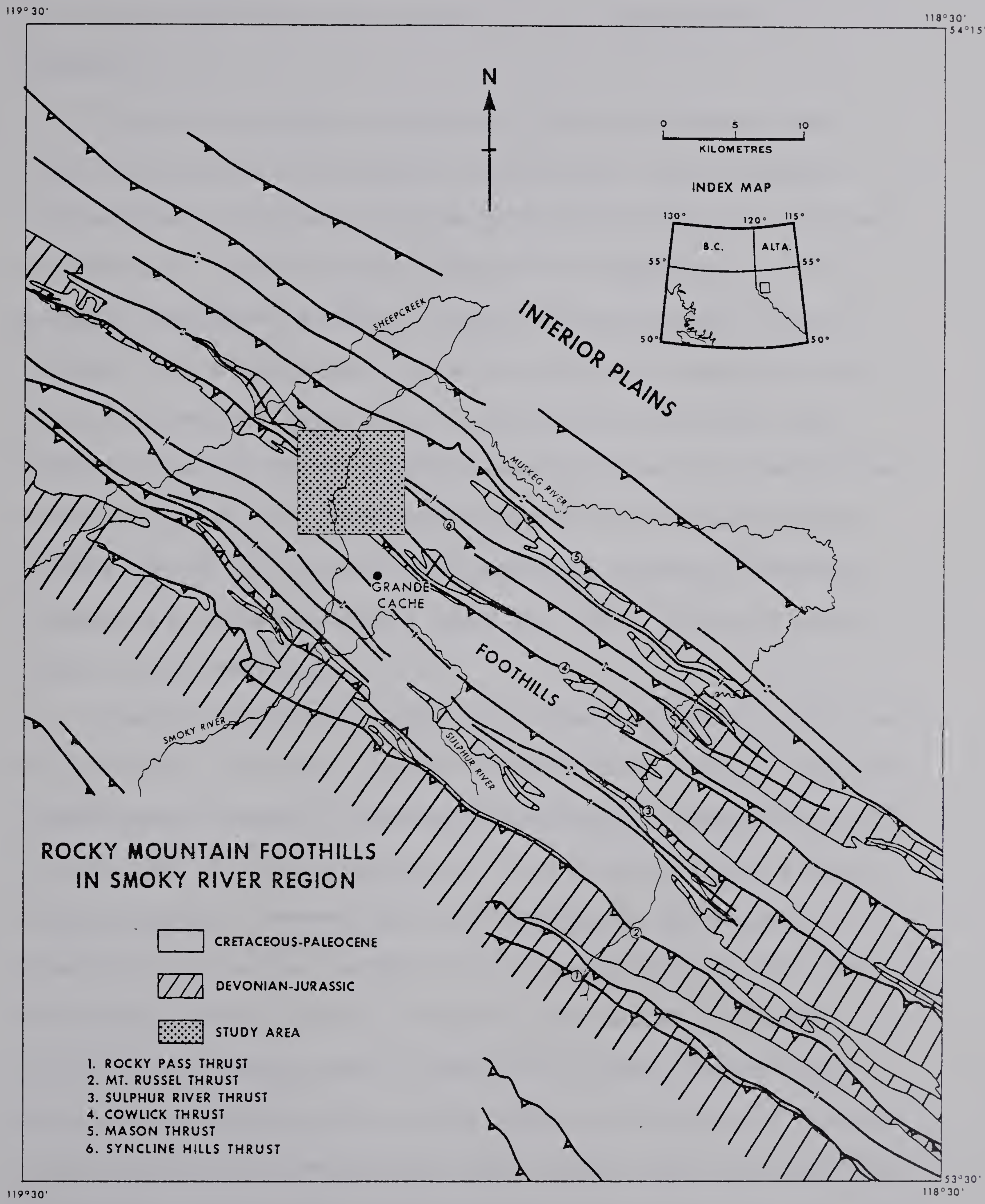

119° 30'
118°30'
54°15'
N
0
5
10
KILOMETRES
INDEX MAP
130°
120°
115°
B.C.
ALTA.
55°
55°
50°
50°
INTERIOR PLAINS
SHEEPCREEK
MUSKEG RIVER
GRANDE CACHE
FOOTHILLS
SMOKY RIVER
SULPHUR RIVER
ROCKY MOUNTAIN FOOTHILLS IN SMOKY RIVER REGION
CRETACEOUS-PALEOCENE
DEVONIAN-JURASSIC
STUDY AREA
1. ROCKY PASS THRUST
2. MT. RUSSEL THRUST
3. SULPHUR RIVER THRUST
4. COWLICK THRUST
5. MASON THRUST
6. SYNCLINE HILLS THRUST
53°30'
119°30'
118°30'

FIGURE 1

summer months, after which ten months were spent in Edmonton as a full-time graduate student at the University of Alberta.

The area studied is near the town of Grande Cache, about 400 km west-northwest of Edmonton. It is readily accessible by Highway 40 from Hinton and there is a gravel airstrip at Grande Cache suitable for light planes. The Alberta Resources Railway from Hinton to Grande Prairie crosses the northwestern part of the area. Access to the northern part of the area is provided by the road from Grande Cache to the McIntyre Mines plant on the Smoky River, whereas Highway 40 provides access to the southern part. Within the 60 sq km of the area itself there are several exploration roads suitable only for trail bikes or four-wheel drive vehicles.

Dominating the area are Mount Hamell (2129 m) just west of the study area and Grande Mountain (1987 m) in the south. Topographic relief is greatest and bedrock exposure best on the slopes of the valley of the Smoky River which flows northeastwards between the two mountains, and whose elevation is as low as 930 m. The topography of the sides of the Smoky River valley is rugged with narrow tributary valleys and steep-sloped intervening spurs. Beyond the watersheds enclosing the Smoky River the relief is generally more subdued, the vegetation much denser, and outcrops more scattered. Vegetation is also controlled by elevation. Below 1000 m, trembling aspen are indicative of an immature

montane rather than a coniferous montane forest which is normally characteristic of these elevations. Small areas of muskeg, vegetated by black spruce, willow, birch and an assortment of grasses, are present where drainage is poor. As the elevation increases to 1500 m the vegetation consists increasingly of species typical to the montane forest ecological zone, namely an assortment of conifers, shrubs, herbs and grasses. Above the montane forest, sub-alpine to alpine vegetation is predominant. This zone is characterized by small conifers and by some shrubs and grasses. Alpine meadows are common on the flatter ridge tops. The conifers end at appoximately 1900 m and above this the sensitive alpine tundra environment is encountered intermixed with areas of barren rock.

The region has already been mapped on a reconnaissance scale by the Geological Survey of Canada (MacVicar, 1917,1920,1924; Irish, 1950,1952,1957,1965; Thorsteinsson, 1952; Stott, 1960,1968,1973). MacVicar (1917,1920,1924) and Irish (1965) provided brief accounts of the history of the area. Other studies that include the Grande Cache area were published by McEvoy (1925) and McLean (1977). Coal leases for the area are held by the Coal Division of McIntyre Mines Ltd. who conducted exploration work during the late 1950's and early 1960's, and also from 1969 to 1975 (Landes, 1962; Brown, 1971). A number of boreholes and adits were completed as part of this exploration.

DATA COLLECTION, RETRIEVAL AND PROCESSING

Field Data

Structural and stratigraphic data were collected in the field by finding outcrops, plotting their positions on aerial photographs and recording various observations made at each outcrop. In addition certain stratigraphic horizons were followed on the ground and with the aid of stereoscopic pairs of photographs and their traces marked on enlarged aerial photographs. The surface traces of formation boundaries, recognizable stratigraphic horizons, faults and axial planes of folds were mapped on the photos and then transferred to the base map. These features were continually modified and updated as more information became available and knowledge of the structure and stratigraphy of the area improved.

Access to the outcrops was largely by foot along traverses beginning on the main road through the Smoky River valley. Midway through the field season a Honda 90 trail bike and a Ford 4-wheel drive truck enabled the more remote areas to be reached using exploration roads.

Aerial photographs were obtained from the Alberta Department of Energy and Natural Resources. The original photographs, taken in 1970 and printed at a scale of 1:18000, provided stereoscopic coverage, whereas enlargements at a scale of 1:9000 were used in the field. Topographic maps on a scale of 1:6000 with a contour interval of 10 ft and a 1000 ft rectilinear north-south, east-west reference grid were prepared by Western Photogrammetry Ltd. in Edmonton.

Throughout this study considerable emphasis was placed on using computer-based techniques to store, retrieve and analyse structural and other data. From the outset field data were collected following a systematic and concise procedure that was applicable to every outcrop visited. To facilitate collection and computerization, as many field data as possible were recorded in numeric code on 80-space sheets (Fig. 2).

Outcrops were numbered consecutively, each number being entered in columns 1-4. Altogether 800 outcrops were visited. Columns 5-8, designed for borehole identification, were not used during field data collection. A binary code indicating (1) the formation and if possible (2) the recognizable stratigraphic interval within the formation was entered in columns 9-10 (Appendix 1). Where possible the stratigraphic distance in feet of the exposed horizon above the base of the formation to which it belongs was entered in columns 11-14. Each outcrop was located as precisely as

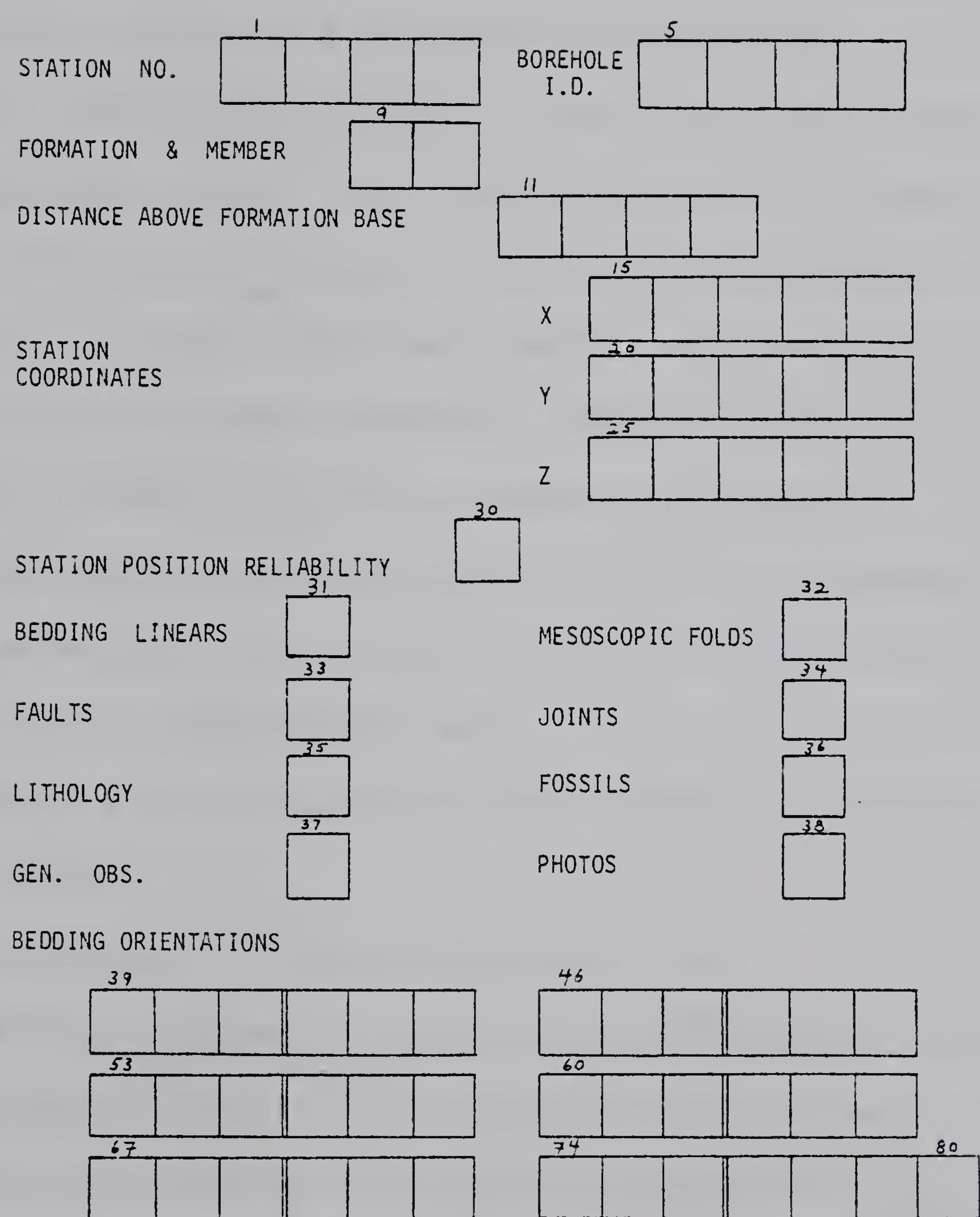


FIGURE 2. Field data sheet for collecting outcrop information.

possible and then marked by a pinhole and the location identified on the back of the appropriate 1:9000 photo. After each outcrop location had been transferred to the topographic base map, its coordinates in feet were obtained and recorded in columns 15-29 of the appropriate field data sheet. The X and Y coordinates, referred to horizontal axes pointing due east and due north, respectively, with an origin at the UTM grid point 19,600,000N and 150,000E of the 120th meridian, were found with the aid of the rectilinear grid, a Douglas protractor and an engineer's scale. The Z coordinate, in feet above sea-level, was measured by interpolating between contours. Errors in the coordinates of an outcrop stemmed from four possible sources:

1. Locating the outcrop incorrectly on the aerial photo.
2. Transferring the outcrop incorrectly from the aerial photo to the topographic map.
3. Reading the coordinates incorrectly from the topographic map.
4. Inaccuracies in the topographic map.

The first three types of error combined normally should not be more than 33 ft (10 m); the fourth is unlikely to exceed 6 ft (2 m). The likely error in the position of an outcrop as given by its coordinates was estimated in feet, divided by ten and placed in column 30.

At each outcrop up to six bedding plane orientations were measured within an area of 10 sq m and recorded in columns 15-29 of the data sheet. Planar orientation data

were measured as numerical dip-direction and dip with a Freiberger compass scaled in grads rather than degrees.

The presence of additional information recorded in a conventional field notebook was indicated on the field data sheet by a 1=yes or 0=no entry in columns 31-38 (Appendix 1). Such information concerned (a) the orientations of bedding plane linears, mesoscopic folds, faults and joints, (b) lithologic descriptions, (c) fossils, (d) general observations and (e) photographs. Where bedding plane linears were observed, the orientations were recorded as multiple readings of the pitches of these linears measured clockwise on the bedding plane. At outcrops displaying mesoscopic folds, as wide a range as possible of bedding orientations was recorded along with the orientation of the axial plane. Multiple readings of fault and joint plane orientations were recorded as numerical dip-direction and dip along with the pitches of any associated slickensides. Repetitive cleat plane orientations were obtained at some of the coal outcrops. Both 35 mm slides and Kodak EK-6 instant pictures were taken in the field. The EK-6 pictures were extremely useful for drawing on and noting field observations, but the camera itself was cumbersome and the pictures were generally of poor quality.

The data sheets were very convenient to use but could be improved by a few minor modifications. The borehole identification could be incorporated into the station number entry and the spaces between the bedding orientations

eliminated. In place of these the date and codes indicating the weather conditions, time of day and mesoscopic fold geometry could be included. Fold information could be subdivided into four separate entries: (a) type of folding - anticline, syncline, monocline or series of folds; (b) orientation of the fold - upright horizontal, upright plunging, vertical, inclined horizontal, inclined plunging, recumbent or reclined; (c) style of folded surfaces - chevron, box or rounded; and, (d) style of folded layers - parallel or similar. This would provide the geologist with a very accessible index on the geometry of mesoscopic folds. It would also be possible to examine the productivity of the geologist under various weather conditions and times of the day and monitor changes in productivity throughout the field season.

Borehole Data

Borehole data in the thesis area are few and generally of poor quality. Although 6 of the 49 boreholes examined had gamma ray and density logs, only elevations and written descriptions of the intersected coal seams were available in the case of the remaining 43 boreholes. Borehole deviation was generally taken into account in calculating the X, Y and Z coordinates of the coal intersections. However, 10 of

these boreholes drilled on Grande Mountain were not provided with deviation records. Although these holes were assumed to be vertical, with bedding dipping approximately 20 NE and the drillholes being up to 300 m long, some deviation from this orientation is to be expected.

During previous exploration, approximately 10 adits were driven for bulk sampling of the coal. For this study the adits served only as artificial outcrops of the coal seams.

Construction and Preliminary Processing of Data Files

The first step upon arrival back at the university was to construct a master data file containing all the codeable and numeric information in an accessible form for retrieval and processing. A master file DATA was constructed by reading computer punch cards prepared from the 800 outcrop data sheets. The format of all but the first and last lines of DATA is identical to the field data sheets with column numbers in the file equivalent to spaces on the data sheets (see Appendix 1).

The storage file BOREHOLE, containing important stratigraphic intersections and the borehole surface locations was constructed from the borehole information (see Appendix 2). The coordinates of the intersections of faults

and the tops of coal seams and the Cadomin Formation were calculated from borehole surface coordinates, borehole orientation and deviation and drilled depths.

The field data contained in the file DATA were partially processed and stored in the file MEANN whose format was acceptable as input to the domain analysis computer packages available in the Department of Geology. The file DATA was first sorted, by the systems package *SORT*, according to stratigraphic code and was input to the program DELET. Using a series of temporary files and the programs SORT, MEANS and RESORT, the file MEANN was then constructed (Fig. 3).

The program DELET (Appendix 3) converts the orientation data measured in grads to degrees, assigns a letter to each stratigraphic interval and places the output in a temporary file -DATA1. The program SORT (Appendix 3) using -DATA1 as input constructs a temporary file -DATA2 containing the repetitive bedding orientations at each outcrop in a format acceptable as input to the program MEANS (available in the Department of Geology). A mean bedding orientation for each outcrop is calculated by this program through a process of vector addition of the direction cosines of the poles to bedding and correcting the resultant mean vector to unity. Fisher's concentration parameter K, which measures the scatter of the bedding orientations measured at each outcrop, is also calculated (Mardia, 1972, p. 251). K values calculated from outcrop data in the thesis area ranged from

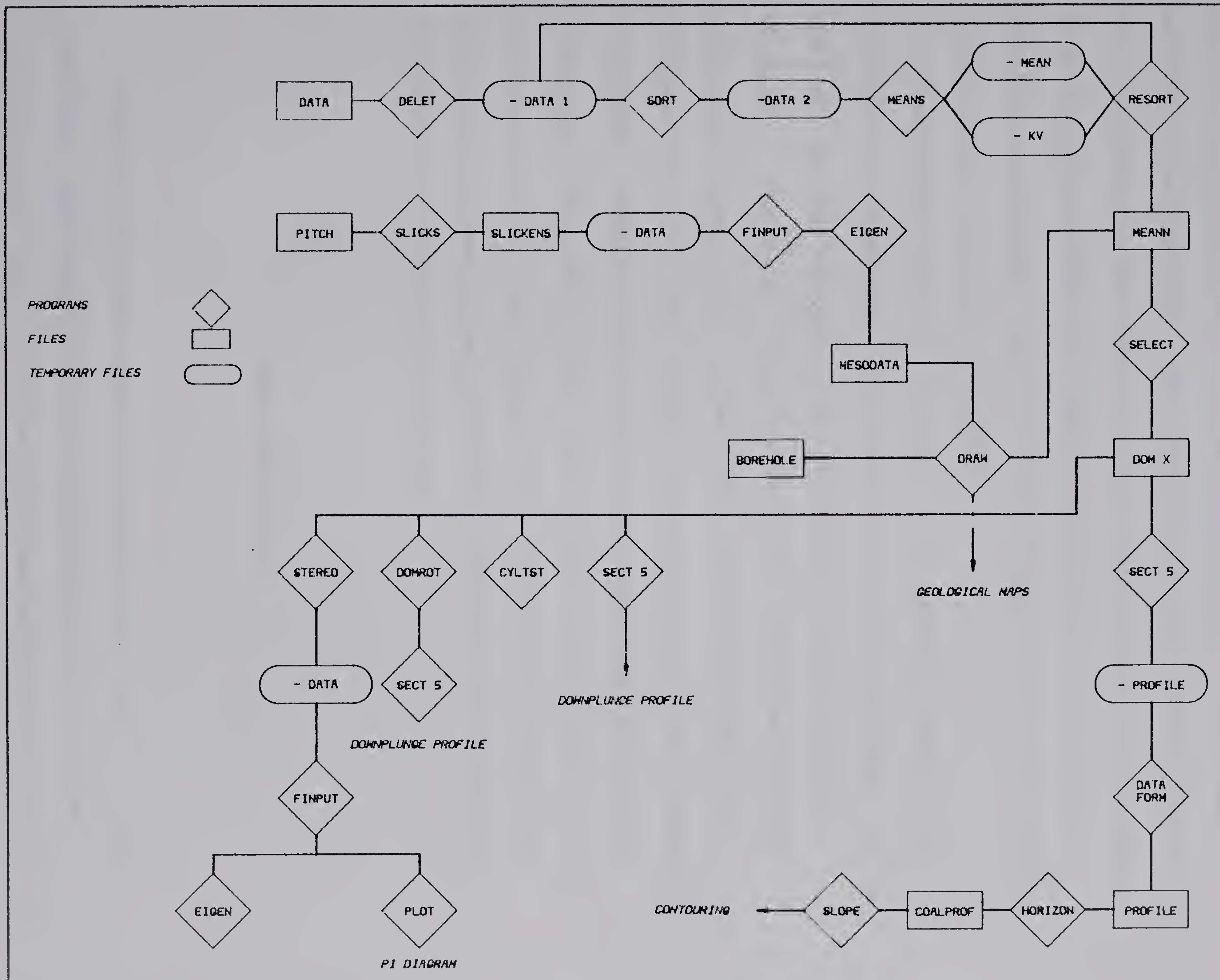


FIGURE 3 : FLOW DIAGRAM OF PROCEDURES FOR DATA PROCESSING

about 30 (indicating a scatter in orientations) to over 40,000 (suggesting very little difference in individual bedding orientations). The output from the program MEANS (in the temporary files -MEAN and -KV) along with certain data from the file -DATA1 are then rearranged by the program RESORT (Appendix 3) and the output placed in the file MEANN whose format is given in Appendix 4.

Geological maps (e.g. Fig. 4, in pocket) showing the locations of outcrops, mean bedding orientations and, as an option, outcrop numbers, were produced on the Calcomp Plotter or Tectronix Graphics Terminal using the program DRAW (see Appendix 5). Input data for this program were obtained from the file MEANN. Similar maps showing borehole locations, bedding plane striae and mesoscopic fold-axes were also produced by DRAW. The format of the input data is the same in each case except that the dip-directions and dips are replaced by zeros for boreholes or by trends and plunges for striae and fold-axes.

Data Retrieval

Two methods were used to retrieve data from the file MEANN and rearrange them in a form amenable to further processing and analysis. The first method involved using the program SELECT (see Appendix 3) to retrieve information by

outcrop number. One of the input files contained the desired outcrop numbers and the second the data from which information was to be retrieved. The format of SELECT had to be modified as different data were required from different files. The second method of data retrieval was by means of the file editor and copy commands. In most instances the data files were sorted according to some parameter before editing or copying took place. During later stages of structural analysis, the domain files were edited and the appropriate borehole information was inserted.

Data Processing

Determination of Cylindricity

Using the geological map and a qualitative knowledge of the structural geology of the area, domains were delineated within which folding was expected to be cylindrical. Separate domain files whose format was identical to MEANN and BOREHOLE and containing all the outcrop and borehole data for each domain were constructed using both data retrieval techniques and then analysed for cylindrical folding.

Individual domains were processed initially by the program CYLTEST, available in the Department of Geology, which determines a best-fit fold-axis and some statistical

parameters that are used in testing for cylindricity. The vector of direction cosines of the pole to bedding is determined for each outcrop in a domain. The column vector of direction cosines for each bedding pole is then postmultiplied by the row vector and the products are summed to form a symmetric 3x3 matrix which has three eigen values and associated eigen vectors. If ϕ_i is the angle between the ith of p poles to bedding and an estimated fold-axis, the best fit fold-axis is obtained when $\sum_{i=1}^{n} \cos^2\phi_i$ is minimized. This minimized sum of squares of $\cos^2\phi_i$ is equal to the minimum eigen value (λ_3) and the associated 3-element eigen vector contains the direction cosines of the best-fit fold-axis (e.g. Cruden, 1968, p. 143-148).

For a perfectly cylindrical fold, with no scatter of bedding poles about the plane normal to the fold-axis, the value of λ_3 is 0. Because of measurement error and bedding plane roughness on a scale less than that of the folding being investigated, this ideal situation is unlikely to be encountered, even in the case of cylindrical folds. Two statistical tests are used to determine the likelihood of the observed scatter of bedding poles being due to non-cylindricity (e.g. Charlesworth <u>et al</u>, 1976).

1. The coplanarity test determines the likelihood of the deviation from cylindricity being due to measurement error and bedding plane roughness on a scale less than that of an individual outcrop. Fisher's concentration parameter (K) and $\lambda^1{}_3$ derived from single randomly

selected original bedding orientations, 1 per outcrop, are required to determine a chi-square statistic used to test the null hypothesis of cylindrical folding.

2. The coaxiality test determines the likelihood of the deviation from cylindricity being due to measurement error and bedding plane roughness on a scale larger than that of an outcrop. Each domain is divided into two segments (a and b) with p_a and p_b outcrops and two values of λ_3 ($\lambda 3_a$ and $\lambda 3_b$) and the respective fold-axes are determined. To accept the cylindrical model two conditions must be met: first, the scatter of poles in each segment about planes normal to the respective fold-axes must be equal and, second, the deviation from cylindricity for the entire domain must be accounted for by the deviation from cylindricity in the two segments.

For practical purposes the results of these two tests are useful but should not be rigorously adhered to when accepting or rejecting the cylindrical model. Other criteria include (a) the relative values of λ_1, λ_2 and λ_3, (b) the value of the standard scattering angle - the standard deviation of the angles between the bedding poles and the plane normal to the fold-axis, and (c) the value of the angle between the fold-axes of different segments of the domain (Kilby, 1978, p. 26-29). Throughout this study cylindricity was assumed when:

1. λ_2 was less than an order of magnitude smaller than λ_1 and more than an order of magnitude larger than λ_3 ;

2. the standard scattering angle was less than 6°;

3. the angle between the fold-axes of separate segments of a domain was less than 5°; and

4. the null hypothesis of cylindricity associated with one of the statistical tests could not be rejected.

Profiles and Composite Sections

The program SECT5, available in the Department of Geology, was used to obtain plots showing for each domain down plunge projections of outcrops and borehole intersections within the domain (see Appendix 6). Input to SECT5 consists of the domain file containing station locations and bedding orientations, the fold-axis orientation, the normal to the plane of projection and a scaling factor to determine the size of the plot. These plots can then be used to construct profiles and sections of any orientation (Fig. 5). For each data observation point in the input file, the program SECT5 transforms the map coordinates to profile coordinates (X and Y) and calculates the pitch of bedding on the profile. At each location on the plane of the profile a short line to represent the pitch of bedding and an identification symbol, present in column 1 of the input file, are drawn by the Calcomp Plotter or Tectronix Graphics Terminal. Locations without bedding orientations are represented by a cross rather than a line. Additional X, Y and Z coordinates of coal seams were read

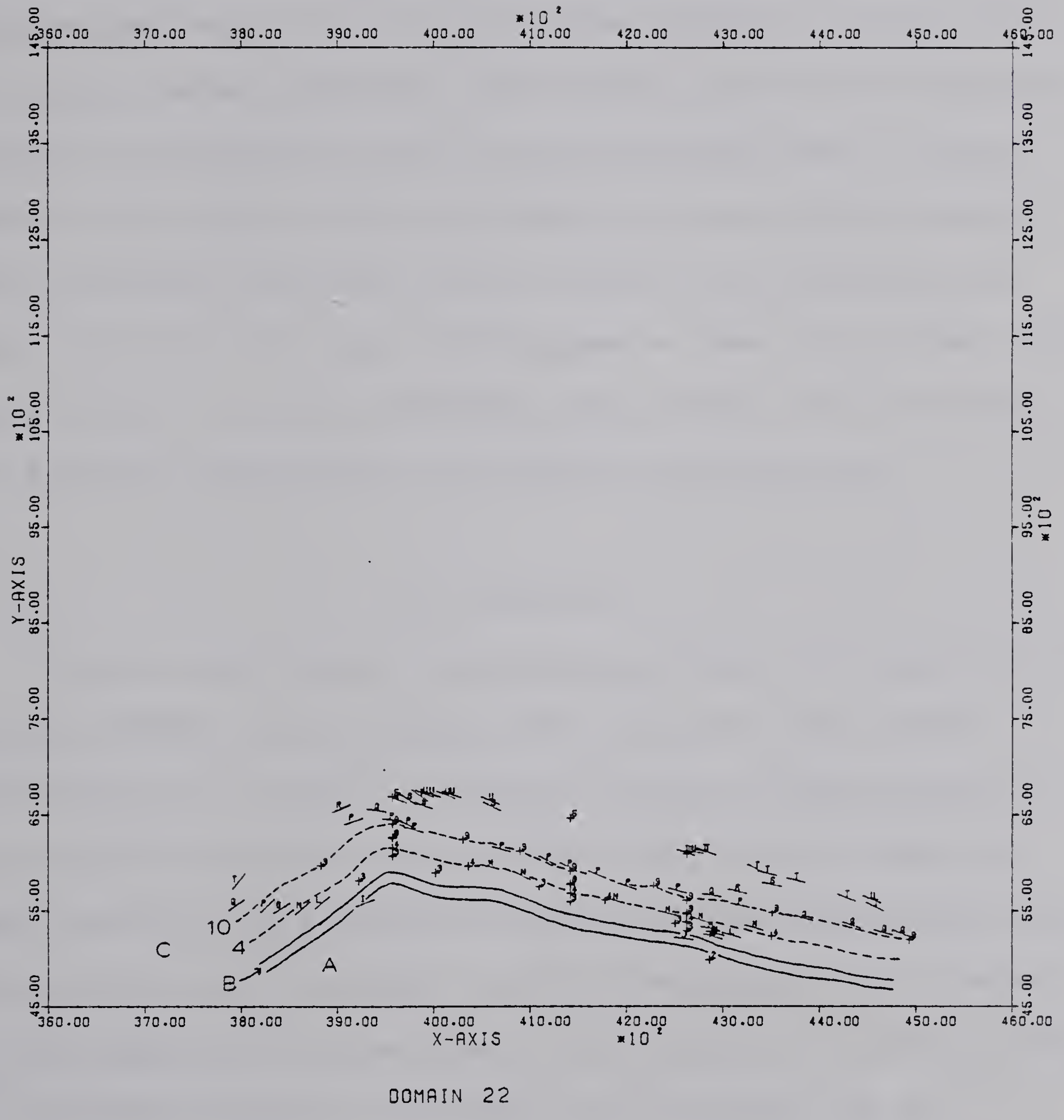


FIGURE 5. Downplunge projection of domain 22 with Luscar Units A, B, and C, and #4 and #10 coal seams.

from the geological map and the locations plotted as outcrops without orientations.

Composite plots for several domains were ultimately constructed using the programs DOMROT, available in the Department of Geology, and SECT5. The domains to be represented were first rotated using DOMROT so that their fold-axes became parallel. The various rotated outcrops and borehole intersections were then projected onto a single plane using SECT5. Input to DOMROT consists of the domain file containing the data to be rotated, the present and "new" fold-axes and the coordinates of the point about which the rotation is to be performed. The output file contains the rotated coordinates and bedding orientations.

Pi Diagrams

The standard files for domain analysis are input to the program STEREO which returns the temporary file -DATA consisting of a title, an identification of data type and the orientation data. The program FINPUT using -DATA as input returns the direction cosines of the orientation data. The program PLOT produces a grid of numbers, each of which is the equal-area projection of the density of bedding poles at a certain counting location on the surface of the reference hemisphere. The diagram is completed by contouring the grid and enclosing it in a circle whose diameter is 8 in (see Kilby, 1978, p. 34).

Fold Geometry

The fold-axis orientation in each domain can be determined in one of two ways: (a) by using the program CYLTEST, or (b) by using the program STEREO and the source programs FINPUT and EIGEN, both of which use an eigen value routine (p. 16). The best-fit fold-axis and the pitch of the axial plane measured on the profile normal to the fold-axis (p. 18), are used to define the axial plane orientation. The apical angle can be measured and the limb shape determined from the down plunge projection.

Stratigraphic Thicknesses

The poor exposure in parts of the thesis area made the stratigraphic position of certain outcrops difficult to determine. The APL program THICK, implementing an automated procedure of the Busk technique, was used to calculate approximate stratigraphic thicknesses between pairs of exposures (Kilby, 1978, p. 34-35). The difference between the radii of cylinders with a common axis at the intersection of planes normal to the two bedding planes, and with surfaces passing through the outcrops, is the interval thickness. In situations where the angle between the two bedding planes is less than 5°, the thickness is taken as the perpendicular distance between the planes passing through the two outcrops whose orientation is the mean of that at these outcrops. This method assumes that folding is concentric so in this map area, where the predominant styles

of folding are chevron and rounded chevron with narrow hinge zones, both exposures must be located on the same limb for this technique to be applicable.

Mesoscopic Structural Processing

Mesoscopic information concerning bedding plane striae, mesoscopic folds, mesoscopic faults, joints and the Cadomin-Nikanassin unconformity were collected and subsequently processed and analysed. Approximately 300 orientations of striae on bedding and fault planes were collected at 25 outcrops. Temporary files containing a title in line 1, the bedding or fault plane orientation in the first 6 columns of line 2 and the pitches of the striae in the first 3 columns of the remaining lines were constructed. Each of these temporary files were processed by the program SLICKS (see Appendix 3) with the output going to the file SLICKENS. The output consists of a title in line 1, the data type in line 2 (in this case TYPE=1) and the trend and plunge of the striae in the first 6 columns of all the remaining lines except the last in which an end of data statement is present. The file SLICKENS was then copied to -DATA and processed by the source programs FINPUT and EIGEN. The file MESODATA was constructed containing the X, Y and Z coordinates in columns 2-16, the mean trend and plunge of the linears at each outcrop in columns 18-23 and a 2 in column 80. The trends and plunges of the striae were plotted on a mesoscopic data map by the program DRAW (Fig. 6).

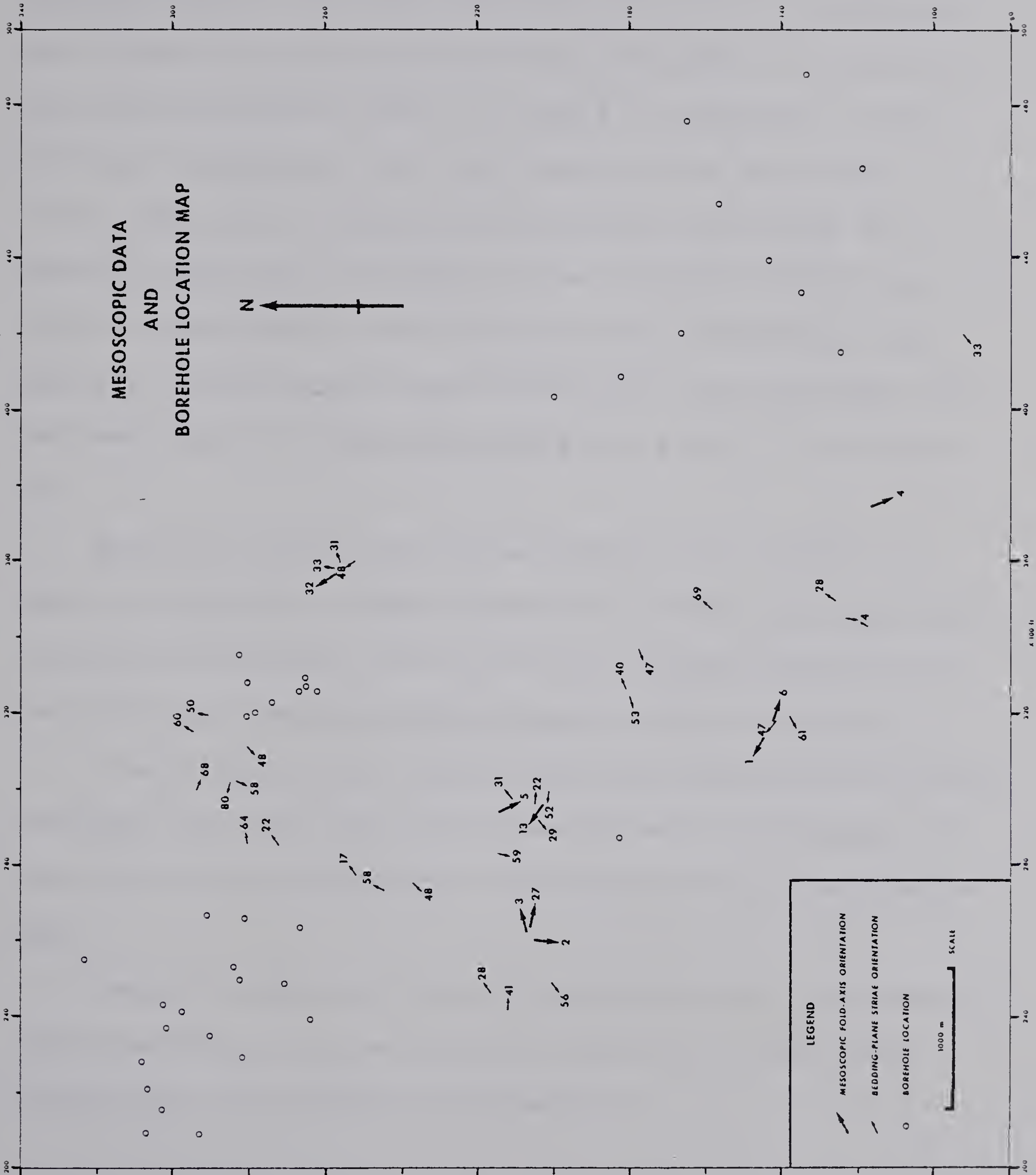

MESOSCOPIC DATA
AND
BOREHOLE LOCATION MAP
N
LEGEND
MESOSCOPIC FOLD-AXIS ORIENTATION
BEDDING-PLANE STRIAE ORIENTATION
BOREHOLE LOCATION
1000 m
SCALE

FIGURE 6

Mesoscopic fold data were of two types: (a) mesoscopic fold-axis orientations, and (b) bedding orientations measured across the folds. Multiple fold-axis orientations were placed in temporary files and processed as linears by the source programs FINPUT and EIGEN to determine a mean fold-axis orientation for each outcrop with mesoscopic folds. Each set of bedding orientations was placed in a temporary file and processed by the programs FINPUT and EIGEN to determine a best fit fold-axis orientation. The fold-axis orientations were put into the file MESODATA with the same format as the striae data but with a 3 in column 80.

Multiple fault planes were processed by FINPUT and EIGEN to determine a mean orientation at each outcrop where faulting was observed. The angularity between bedding and the fault plane was also determined at these outcrops.

A mean joint plane orientation was obtained from FINPUT and EIGEN for each joint set observed and a pi diagram of the joint plane orientations was produced using the program PLOT.

Computer programs written specifically for analyses of structural data included in this thesis are listed with appropriate run commands in Appendix 4.

STRUCTURE CONTOURING

Contour maps showing the configuration of a coal seam and the variation of its depth below the topographic surface are used extensively in coal exploration. A major aim of this thesis was to develop a numerical, computer-based technique for constructing such maps from an input of orientation, positional and stratigraphic data. Most contour maps are constructed, either manually or numerically (e.g. Gold, 1978), from irregular sets of points in two-dimensional space, at each of which the numerical value of the quantity to be contoured is known. However, the above contouring method can be implemented in the case of coal seams only after extensive drilling. What is needed is a method that uses as input an irregular set of outcrops and borehole intersections of known geographic location, stratigraphic position and, in the case of outcrops, bedding orientation.

In the computer-based method of structure contouring from outcrop and borehole data developed by Robinson (1976), coordinates on the horizon to be contoured are estimated by simulation of the known fold geometry within a cylindrical domain. The method developed in this thesis has four steps:

1. division of the area into domains within which the horizon to be contoured is cylindrically folded, and calculation of the fold-axis in each domain;
2. construction of the profile of the horizon to be contoured in each domain;
3. projection of each profile parallel to its fold-axis in order to generate the coordinates of a set of points on the horizon; and
4. computer contouring of the resulting elevations.

The first step has already been dealt with (p. 14) and the fourth is already well known. The second and third steps are described below.

The Profile

Profiles may be constructed either graphically or using a numerical, computer-based procedure. The graphical technique is used where the exact stratigraphic position of most outcrops and borehole intersections is uncertain or where structural complexities require considerable interpretation on the part of the person drawing the profile. The profiles can be drawn on computer plots that show the positions of each outcrop and borehole intersection projected parallel to the fold-axis and where possible the traces of bedding (p. 18). Using as a guide the traces of

bedding and the stratigraphic positions of the outcrops and borehole intersections, a best-fit line representing the trace of the horizon to be contoured is drawn on each plot. The resulting lines are then digitized, generally at irregular distances along the horizontal (X) axis, care being taken to include the hinge and inflection points of any folds, and each digitized point is given equal weight (see below). The pitch of the horizon at each digitized point (X Y) is estimated from the profile.

The numerical method for constructing profiles can be used where the exact stratigraphic position of most outcrops is known and where the fold is either similar or parallel in style. It consists of the following steps:

(1) a computer line file is constructed from the profile coordinates of each outcrop and borehole intersection in the domain projected normally onto the plane of the profile and, where possible, the pitch of the trace of bedding and the precise stratigraphic position. To do this each domain file is processed by SECT5 (p. 18). The profile coordinates and the pitches of bedding from the output file are then combined with the precise stratigraphic positions, outcrop numbers and stratigraphic identifications from the domain file by the program DATAFORM (see Appendix 7).

(2) the profile coordinates, bedding pitch and precise stratigraphic position in each line of the above file are used to determine the profile coordinates (X_i Y_i)

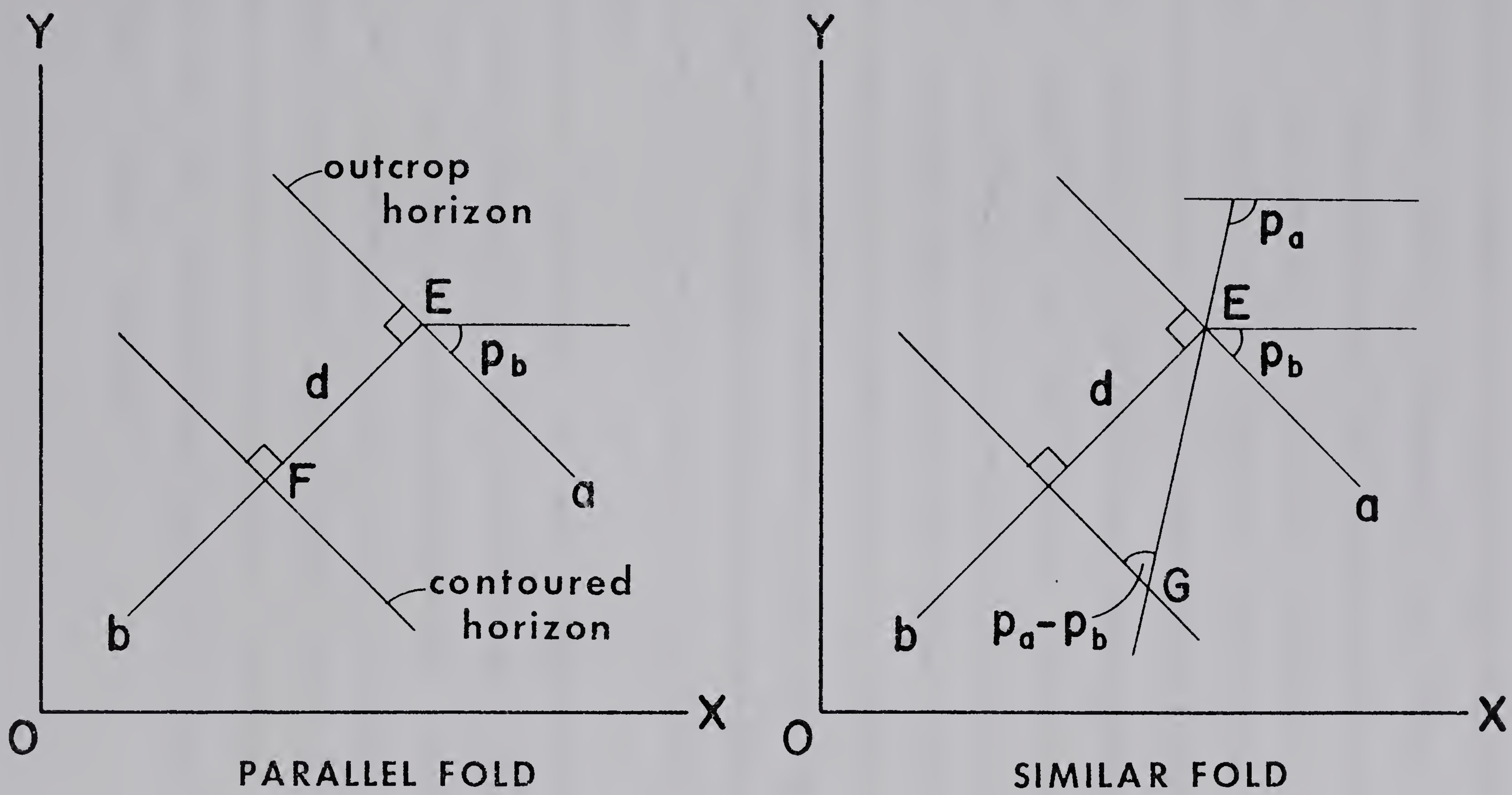
of one point on the horizon to be contoured. In Figure 7, E is the normal projection of an outcrop onto the plane of the profile, i.e. the XY plane. The coordinates of E referred to the axes X Y and the origin O are (x_e y_e). The pitch of bedding measured clockwise on the XY plane is p ° and that of the axial plane is p_b° . The axes a and b intersecting at E have pitches of p_b° and p_b+90°, respectively. From Figure 7, if the horizon exposed at E is a distance d stratigraphically above the horizon to be contoured, the coordinates of a point F on this horizon, referred to the axes a b and to an origin at E, are (0 d) in the case of parallel folding. In the case of similar folding the point corresponding to F is G, and its coordinates are (d÷tan(p -p) d). Using well known transformation equations, the coordinates (x y) of F and (x y) of G referred to the axes X Y and to an origin at E are given by,

$$[M] \times [0\ d]' = [x\ y]'$$

and $$[M]\ [d \div \tan(p - p)\ d]' = [x\ y]'$$

where $$[M] = \begin{matrix} \cos(p_b) & \cos(180-p_b) \\ \cos(270-p_b) & \cos(p_b+90) \end{matrix}$$

The coordinates of F and G referred to the axes X Y and to an origin at O can be obtained by adding x_e y_e to x y and the pitch of bedding at F and G is the same as that



Determination of the position of the coal seam
from positional, orientation and stratigraphic information.

FIGURE 7

at E. Small changes to the above equations are required when $p > 90°$. A weight is calculated based on the stratigraphic interval d separating the outcrop or borehole intersection and the horizon to be contoured.

(3) the points produced in step (2) display a certain amount of scatter about a best-fit line on the profile representing the coal seam. Coordinates and slopes of points lying on this best-fit curve are calculated at regular intervals along the X-axis by projecting the profile coordinates (X_i Y_i) parallel to their slopes to each X increment and weighting each value relative to the distance of the projection along the X-axis and the stratigraphic weight calculated in step (2). The slope at a point on the curve is estimated by weighting the input slopes with the stratigraphic and projection weights.

The procedure of calculating the coordinates of a coal seam on the profile discussed here is by no means a general case. Anyone adopting this approach has to examine the technique closely and, if necessary, modify it to be consistent with the geometry of the folds being studied. Plots showing the positions of points on the coal seam are produced in both steps (2) and (3), unsmoothed and smoothed, respectively (see program HORIZON, Appendix 7).

The Three-dimensional Array

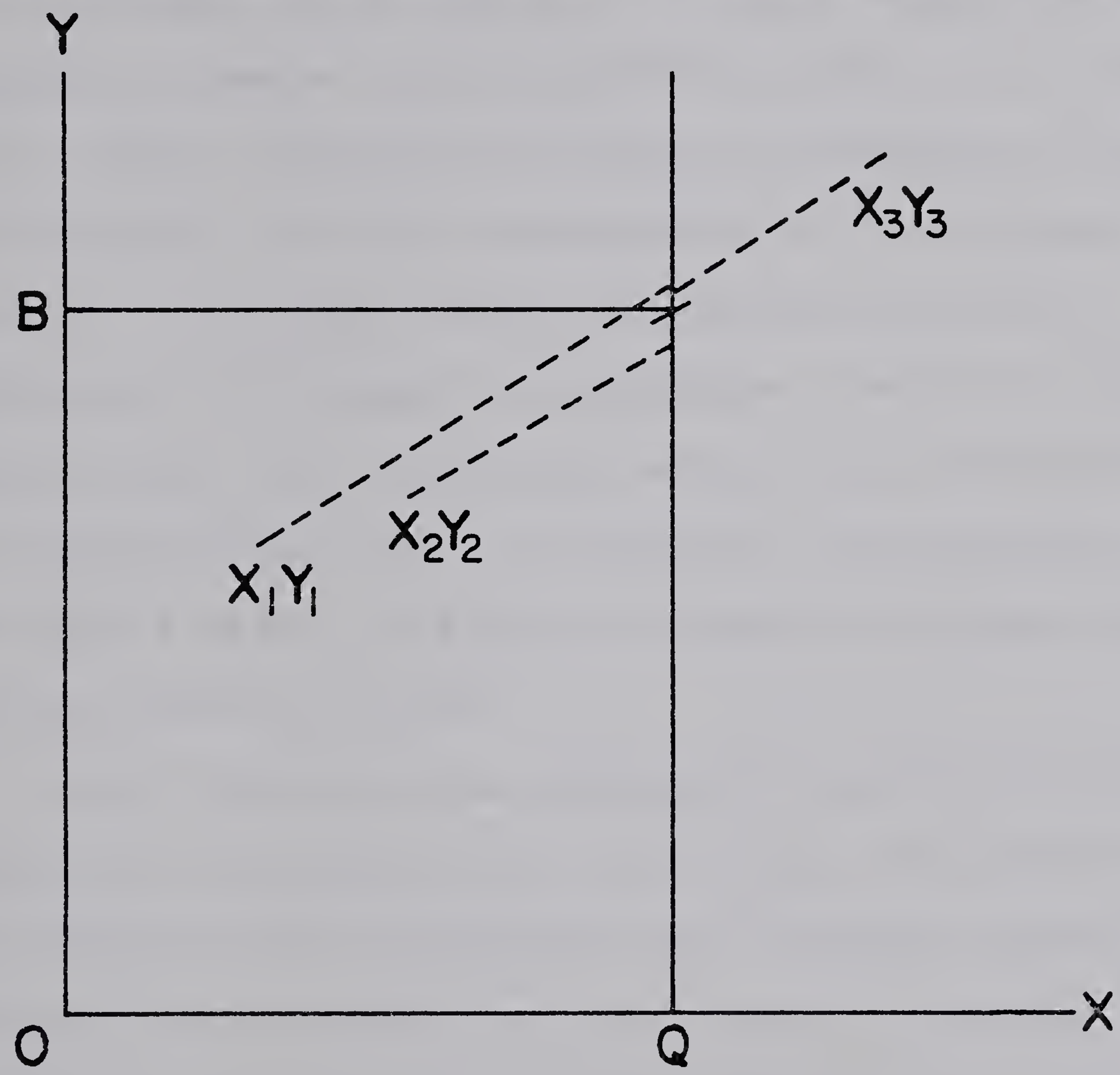
The procedure for extrapolating the profiles to generate three-dimensional sets of points representing elevations and depths is outlined below:

(1) a line file containing the coordinates of a set of points (x y z) on the topographic surface in each domain is built. This array could form a uniform grid and as such would have to be built from scratch using the topographic map of the area. Alternatively the array could be built using the coordinates of outcrops and borehole locations, supplemented by some points along the axial traces of folds, and as such be irregular. The second method was preferred not only because it was less onerous but also because the array of points, used subsequently as input to the contouring procedure itself (see below), is widely spaced where outcrop and borehole control is poor and closely spaced where control is good, as indeed should be the case.

the next step is tc calculate the elevation of the horizon to be contoured directly beneath each of the points (x y z). To do this the program SLOPE (see Appendix 7) is used to find, first, the profile

coordinates (X Y) of the points (x y z) projected normally onto the plane of the profile, and second, the B (Y) value of the horizon to be contoured at the node Q . The horizon is projected from each of its profile points (X_i Y_i) (determined either graphically or numerically) parallel to the individual pitches to the node Q (Fig. 8). A weight is calculated for each projection based upon the distance of the projection along the X-axis. A single point (X B) of the horizon on the profile is calculated using these projections and the stratigraphic and projection weights. This point is the normal projection of the point [x y z-(B/cos p)] where p is the plunge of the fold-axis, so the elevation and depth of coal at the point (x y z) are (z-B)/cos p and B/cos p, respectively. The slope of the horizon beneath the point (x y z) is determined by similarily weighting the individual slopes of the profile points (X_i Y_i) on the coal seam.

A plot of the downplunge projections of the set of points located on the surface of the coal seam is produced. The stratigraphic and projection weights are calculated with the equation $Wt=e^{-Ax}$ (Newton, 1973) where A is a constant and x is the distance between the known and interpolated coordinates. The amount of smoothing and influence of neighbouring points can easily be adjusted by changing the value of A. The maximum possible weight using this procedure is 1.0.



Estimation of the profile coordinates of the coal seam at any node Q from known locations and orientations.

FIGURE 8

Contouring the Three-dimensional Array

The sets of coal seam elevations or depths calculated for each domain were combined for final contouring with a triangular element routine provided by Dr. C. M. Gold (Gold et al, 1977), Department of Geology, University of Alberta. The procedure involves interpolation of the surface within irregular triangular domains constructed from the coordinates and slopes of the horizon provided by the program SLOPE. Each individual array was constructed so as not to overlap but only to border any neighbouring domains and allow a smooth continuum of contours between cylindrical domains (see Fig. 14-19).

These techniques can readily be expanded to produce isopach and stripping ratio maps. Slope calculation at each map location could be modified to a weighted eigen value routine rather than the weighted average presently being used.

STRATIGRAPHY

Some 1250 m of marine and non-marine strata ranging from the Jurassic and Lower Cretaceous Nikanassin Formation to the Upper Cretaceous Kaskapau Formation are exposed in the study area. Lithic sandstone, siltstone and shale are more common than conglomerate and coal. Four major transgressive and three major regressive sequences can be recognized. The transgressive phases are represented by the lower 200 m of the exposed part of the Nikanassin Formation, a marine shale band in the Luscar Formation and the marine shales of the Shaftesbury and Kaskapau Formations. The upper 160 m of the Nikanassin Formation, the Cadomin Formation and lower 95 m of the Luscar Formation constitute one continental regime. The others are represented by the upper 475 m of the Luscar Formation and by the Dunvegan Formation. A number of coal seams are present within the lower 310 m of the Luscar, three of which are of sufficiently high quality and thickness to warrant mining and are currently worked by McIntyre Mines north of the study area.

Nikanassin Formation

Some 365 m of the upper Nikanassin Formation are exposed directly above the Grande Mountain thrust and in the core of the Campbell Anticlinorium. Although no distinct mappable units were encountered, the upper 160 m are non-marine whereas a highly variable flyschoid sequence makes up the remainder of the formation. The main lithologies represented are shale, carbonaceous shale, siltstone and lithic and argillaceous sandstone.

The non-marine sequence contains carbonaceous shale and a few thin lenticular coal bands. Its thin, cross-bedded sandstones are commonly ripple marked and contain a few thin, discontinuous pebbly bands. The marine sequence is composed of sandstone, shale and siltstone from which carbonaceous material, cross-stratification and ripple marks are conspicuously absent. The Jurassic-Cretaceous boundary coincides approximately with the contact between the marine and non-marine sequences. Fossils were collected at one locality: a Jurassic pentacrinus on Packrat Creek, 183 m below the Cadomin Formation. In addition, near the top of the Nikanassin Formation abundant but unidentifiable plant remains were observed.

The Nikanassin is unconformably overlain by the Cadomin Formation (Irish, 1965, p. 54). Using a method similar to that described by Cruden and Charlesworth (1966), bedding orientations from both sides of the unconformity were collected at five localities in an attempt to determine its angularity and the dip-direction of Nikanassin strata in Cadomin time. At one locality there was no significant angularity. Apparent angularities of 28°, 22°, 9° and 8° were observed at the other localities with inferred dip-directions for Nikanassin strata in Cadomin time of 293°, 321°, 72° and 90°, respectively. The absence of angularity at one locality, the large apparent angularities at two localities, and the variation in inferred dip-direction suggest that in fact the sub-Cadomin unconformity is not angular and that the apparent angularities observed at four localities suggest an irregular erosional surface.

Cadomin Formation

The Lower Cretaceous Cadomin Formation, a prominent ridge-forming unit whose thickness varies from 22 to 38 m, is made up of a lower conglomerate (8 to 15 m), a middle sandstone (3 to 6 m) and an upper conglomerate (9 to 18 m). The conglomerates consist of well-rounded chert and quartzite pebbles and cobbles in a medium- to coarse-grained

lithic sandstone matrix. White, grey, black, green, banded and occaisionally red chert makes up approximately 60% of the rock. The quartzite fragments are generally white, buff and pinkish in colour. The lower conglomerate tends to be coarser grained and to have more green chert particles. The conglomerates are silicified and extremely well indurated: fractures generally cut across fragments rather than around them. The medium-grained lithic sandstone contains some fine-grained silty and coaly zones. Poorly preserved plant remains were observed at the base of the formation and in the sandstone member. The upper conglomerate grades into the overlying Luscar Formation within a zone less than 1 m thick.

Luscar Formation

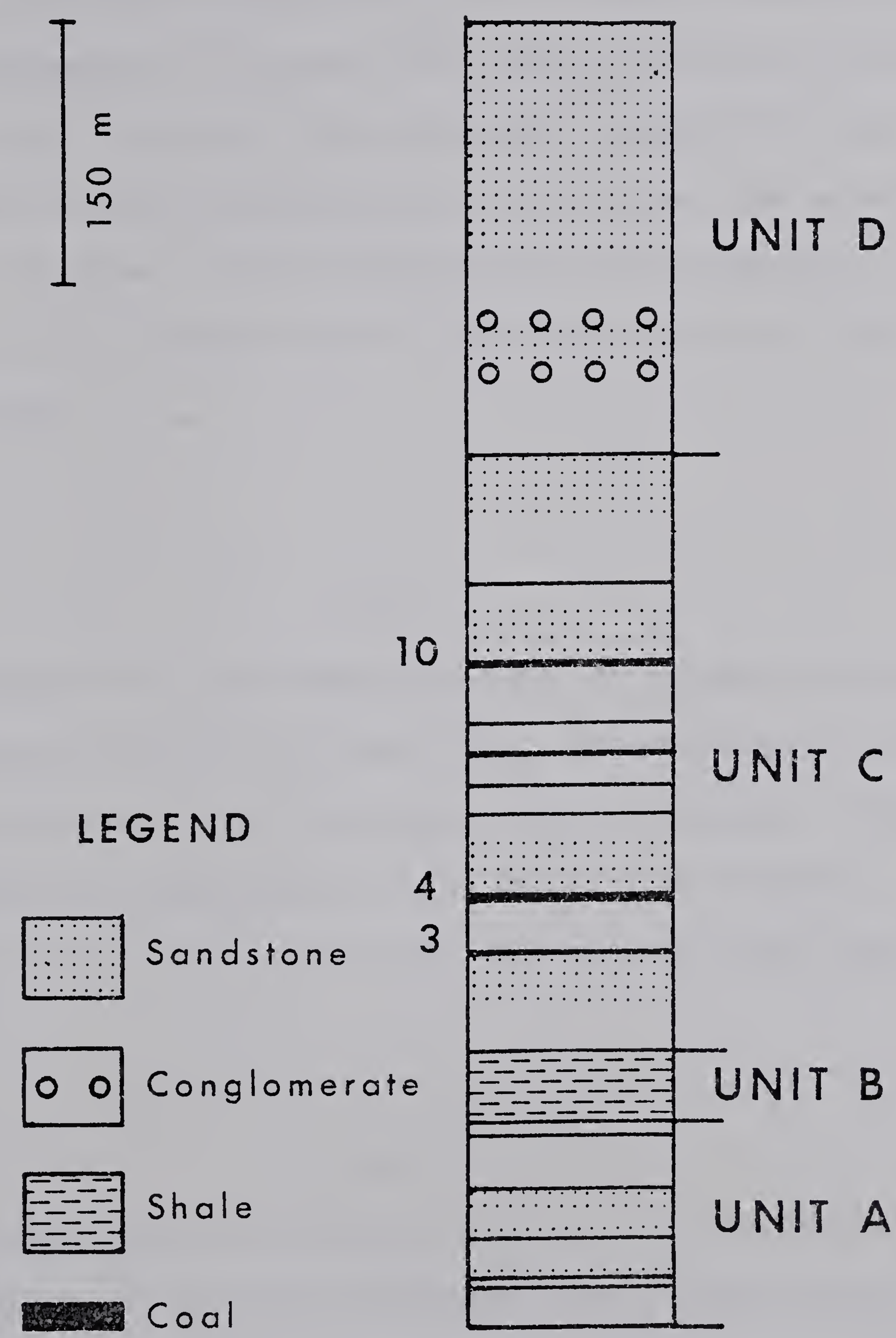
At 550 to 600 m thick, the Luscar Formation is the thickest unit present and underlies more than half the study area. Its lithologies are many and varied and include sandstone, shale, siltstone, conglomerate and coal. Grey and brown, buff weathering, lithic and argillaceous sandstone make up half the formation. The sandstones in the upper 100 m are grey in colour and are thicker bedded than those lower in the formation. Grey to dark grey shale, mudstone and carbonaceous shale comprise one quarter of the formation,

whereas dark grey siltstone accounts for nearly 20%. Approximately 2.5% of the formation consists of coal seams ranging in thickness from a few centimeters to 4.5 m. Conglomerates account for less than 2% of the formation. Concretionary ironstone bands and nodules associated with shale and siltstone occur in minor amounts. Practically all the coal occurs within the lower 310 m and most of the conglomerates within the lower 95 m of the formation. Although no complete section through the formation is exposed, a composite section based primarily on exposures along Packrat Creek and Hells Creek has been established and is included as Appendix 8.

Four map units, established by the author, are present within the formation (Fig. 9) and are described below. Although the thicknesses and facies of the horizons within these units vary somewhat, in general they are continuous over most of the area. Measurements of the thicknesses of the units at different localities, although too few to obtain a definite rate and direction of thinning, are consistent with a northeasterly direction of thinning. The numbering of the coal seams given below is that used by McIntyre Mines.

Unit A

Coal seam #1, 1.2 to 1.8 m thick, occurs 20 m above the base of the formation and is directly overlain by a resistant 4.6 m thick sandstone and conglomerate bed. Coal



Stratigraphic column of the Luscar Formation

FIGURE 9

W, up to 0.8 m thick, may be present about 3 m below the #1 seam. Coal X, also less than 1 m thick, may be present about 45 m above the formation base and is overlain by a 7 m thick sandstone and conglomerate bed. A 7 m thick, massive, fine-grained sandstone is located 60 m above the base of the formation and 3 m above this the 0.5 m thick #1.5 coal may be present. Located approximately 85 m above the base is the 1 m thick #2 seam. The thicknesses and stratigraphic positions of all except the #1 seam were obtained from borehole data.

Unit B

Located 91 m above the base is a 31 m thick section of marine mudstone and shale with thin, cross-bedded, fine-grained sandstones and rare hard, nodular, silty, orange-brown weathering mudstones. This unit is of uniform thickness and is persistent over the entire study area.

Unit C

The most distinct marker horizon in the formation is a ridge-forming, 15 to 20 m thick sandstone which occurs about 150 m above the base. The sandstone, referred to locally as the 'Salt and Pepper Sandstone', is medium-grained, lithic and weathers to a light grey with some reddish-brown limonite staining. Coal seam #3, 1 to 1.8 m thick, directly

overlies the sandstone and a 1.5 to 7.5 m thick pelecypod coquina, referred to locally as the 'Clam Zone', begins 1.5 m above the coal. Coal seam #4 is located nearly 200 m above the base. It ranges in thickness from about 4 m on the northwest side of the Smoky River to between 3 and 3.3 m on the southeast side, and reaches a maximum thickness of over 6 m just north of the study area. A massive, fine-grained and silty sandstone referred to locally as the 'Super 4 Sandstone' occurs 3 m above #4 seam. Along Two Camp Anticline this sandstone reaches a maximum thickness of 24 m. It is characterized by rapid facies changes, and at some localities it is absent and replaced by a silty and shaly sequence. Located about 230 m above the base is the discontinuous 0.2 m thick #5 seam which is of no value as a marker horizon and was identified in only a few boreholes. Coal seams #6 and #7, also discontinuous with thicknesses up to 1.2 m and separated by 0 to 1.2 m of mudstone, are located about 240 m above the base. Seam #8, from 3 to 10.7 m above coal #7, has a thickness of 1 to 1.4 m. The stratigraphic interval between #4 and #8 seams thins from 50 m on Mount Hamell to 35 m on Grande Mountain. Located about 295 m above the base is seam #10 (previously named #9 by Landes, 1962) which ranges in thickness from 1 to 3 m.

At 300 m and 360 m above the base of the formation are two medium- to fine-grained lithic sandstones, ranging in thickness from 15 to 24 m and 12 to 21 m, respectively. The shaly strata separating these sandstones are by no means

uniform in thickness, as evidenced by borehole 6118 (26596E 28105N), located on Campbell Flats, where the shales are absent and the combined thickness of the sandstones is 36 m. The sandstones weather light grey with large oval, reddish-brown, limonite stains. Despite being only poorly indurated, the sandstones generally form prominent ridges.

Unit D

Unit D is represented by upper 160 to 180 m of the formation. A granular and pebbly sandstone with a thickness of 18 to 25 m is located about 400 m above the base and 160 m below the top of the formation. It consists of a lower granular section (7.6 m), an intervening medium-grained sandstone (5 to 10 m) and an upper granular and pebbly sandstone (6.1 m).

Fossils

With the exception of the upper 120 m, plant fossils and remains are abundant throughout the formation. In addition to plant fossils, the following important collections of pelecypods and gastropods were made.

1. Pelecypods were collected from the coquina horizon locally referred to as the 'Clam Zone'. This interval is widely distributed and can be found overlying the #3 coal throughout the entire study area.
2. On Grande Mountain (map reference 37941E 14461N),

very well preserved specimens of the pelecypod Unio and some gastropods were collected along a road cut about 6 m above the #4 seam, 200 m above the formation base, from the silty facies equivalent to the 'Super 4 Sandstone'.

3. On Grande Mountain (map reference 37826E 11037N), approximately 470 m above the base, some gastropods and pelecypods were collected from outcrops along a cliff. This fossil zone is a reliable marker horizon within Unit D and can be identified in borehole samples and at other outcrops.

Regional Stratigraphic Correlation

The marine mudstones and shales located about 90 m above the base of the Luscar Formation probably correlate with the Moosebar Formation of northeastern British Columbia. There, as at Grande Cache, the beds (belonging to the Gething Formation) that underlie the marine shales differ from the overlying strata (belonging to the Gates Formation) which have thicker and more abundant coal seams. At Mount Torrens, 65 km to the northwest of Grande Cache, Stott (1968) indicated that the Moosebar Formation is 42 m thick and is located 91 m above the Cadomin Formation. At Grande Cache this shale wedge is significantly thinner than farther north and continues to thin southward (Kilby, 1978).

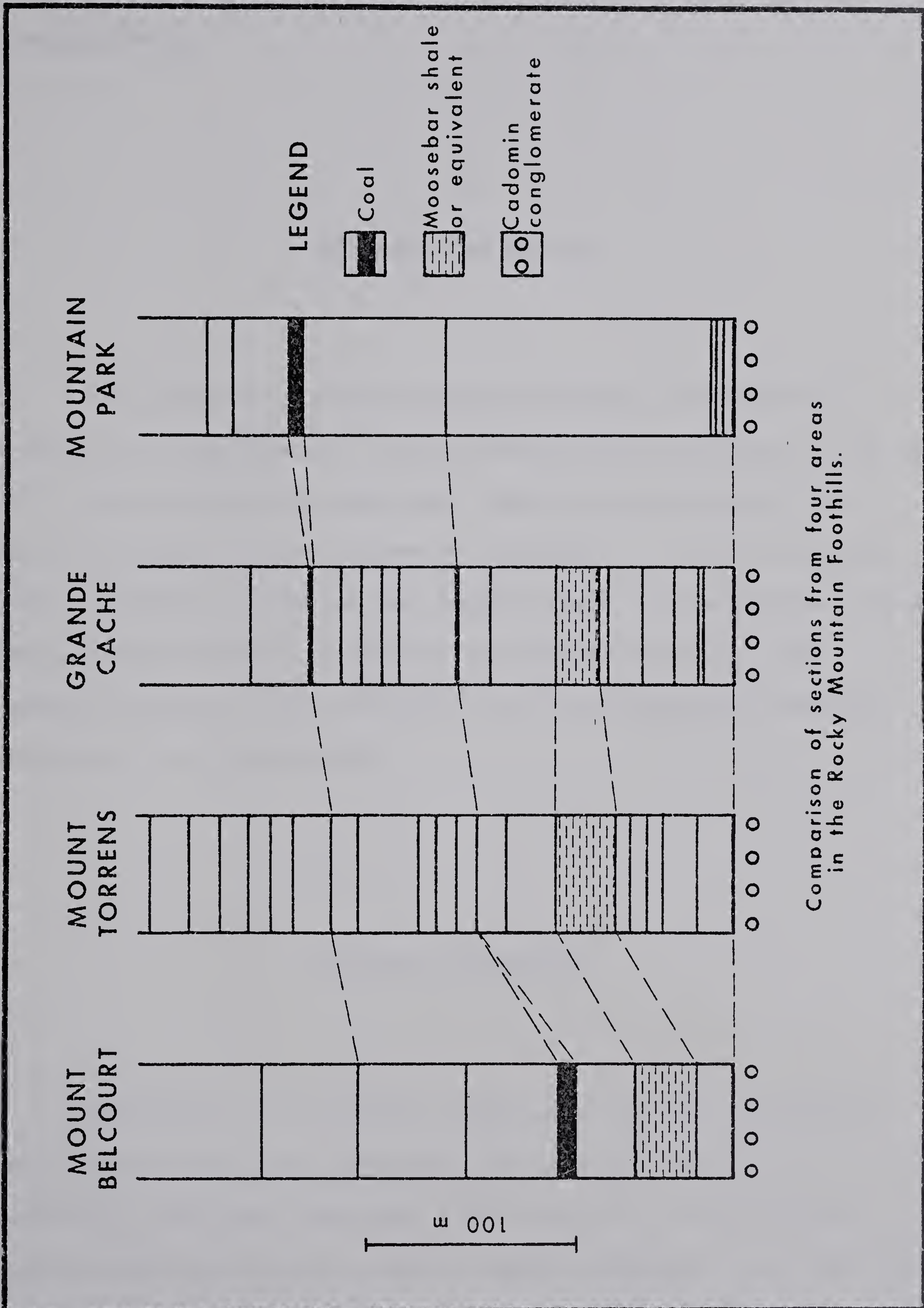
In the central and northern foothills of Alberta, thick

seams observed at several localities occupy similar stratigraphic positions within the Luscar Formation. Kilby (1978) has suggested that these seams may be correlated. Among these seams are the #4 coal seam at Grande Cache, the Jewel Seam at Cadomin and Luscar, the Kennedy Seam at Mountain Park and the thick seam near the base of the Gates Formation at Mount Torrens and Mount Belcourt, 100 km to the northwest of Grande Cache (Fig. 10).

The Mountain Park Formation as described by MacKay (1930) is not distinguishable from the Luscar Formation in this area. However, the uppermost 100 m of the Luscar Formation, composed of non-marine, barren sandstones and siltstones, is possibly equivalent to the Mountain Park Formation.

Shaftesbury Formation

This formation has limited exposure in the study area and is mainly restricted to the Syncline Hills syncline. It consists of 140 m of dark grey, fissile, marine shale commonly with concretionary ironstone bands and some siltstone and sandstone layers. The boundary between the Upper and Lower Cretaceous lies near the top of the formation. The contacts with the underlying Luscar and



Comparison of sections from four areas in the Rocky Mountain Foothills.

FIGURE 10

overlying Dunvegan Formations are sharp and gradational, respectively.

Dunvegan Formation

The resistant, ridge-forming Dunvegan Formation is exposed in the Syncline Hills syncline and consists of 30 to 45 m of interbedded sandstone, shale and siltstone. The basal section of the formation contains a 7.5 to 9 m thick well indurated, massive and blocky quartzose sandstone above which lies the more variable interbedded section. The contact between this formation and the overlying Kaskapau Formation is gradational.

Kaskapau Formation

Exposures of the Upper Cretaceous Kaskapau Formation are restricted to the Syncline Hills syncline and to directly below the Syncline Hills thrust. Its dark grey, thin-bedded and fissile marine shales commonly are silty and contain clay ironstone bands. These shales are very

incompetent and structures involving them are generally complicated by minor faulting and folding, making thickness determinations difficult. However, this formation is believed to attain a maximum thickness of 460 to 500 m (Irish, 1965), of which only the lowest 100 m are present in the study area.

STRUCTURAL GEOLOGY

Strata in the Rocky Mountain Foothills of the Smoky River region are folded and cut by numerous southwesterly dipping thrust faults (Fig. 1). Most of the thesis area is underlain by Nikanassin to Kaskapau strata belonging to the Syncline Hills thrust-sheet. To the southwest these strata are bounded by Nikanassin and younger strata of the Cowlick thrust-sheet and to the northeast by Kaskapau and older strata of the Mason thrust-sheet. The area has been divided into 22 domains within each of which folding can be considered cylindrical (Fig. 11).

Cowlick Thrust-sheet

Traceable for about 100 km along strike, the Cowlick fault is one of the larger thrusts in the Alberta Foothills north of the Athabasca River (Irish, 1965). Within the Cowlick thrust-sheet only the Nikanassin and Cadomin Formations between Mount Hamell and Grande Mountain were mapped. The fault has a dip of approximately 60° SW beneath Mount Hamell, steepening to about 70° SW on Grande Mountain,

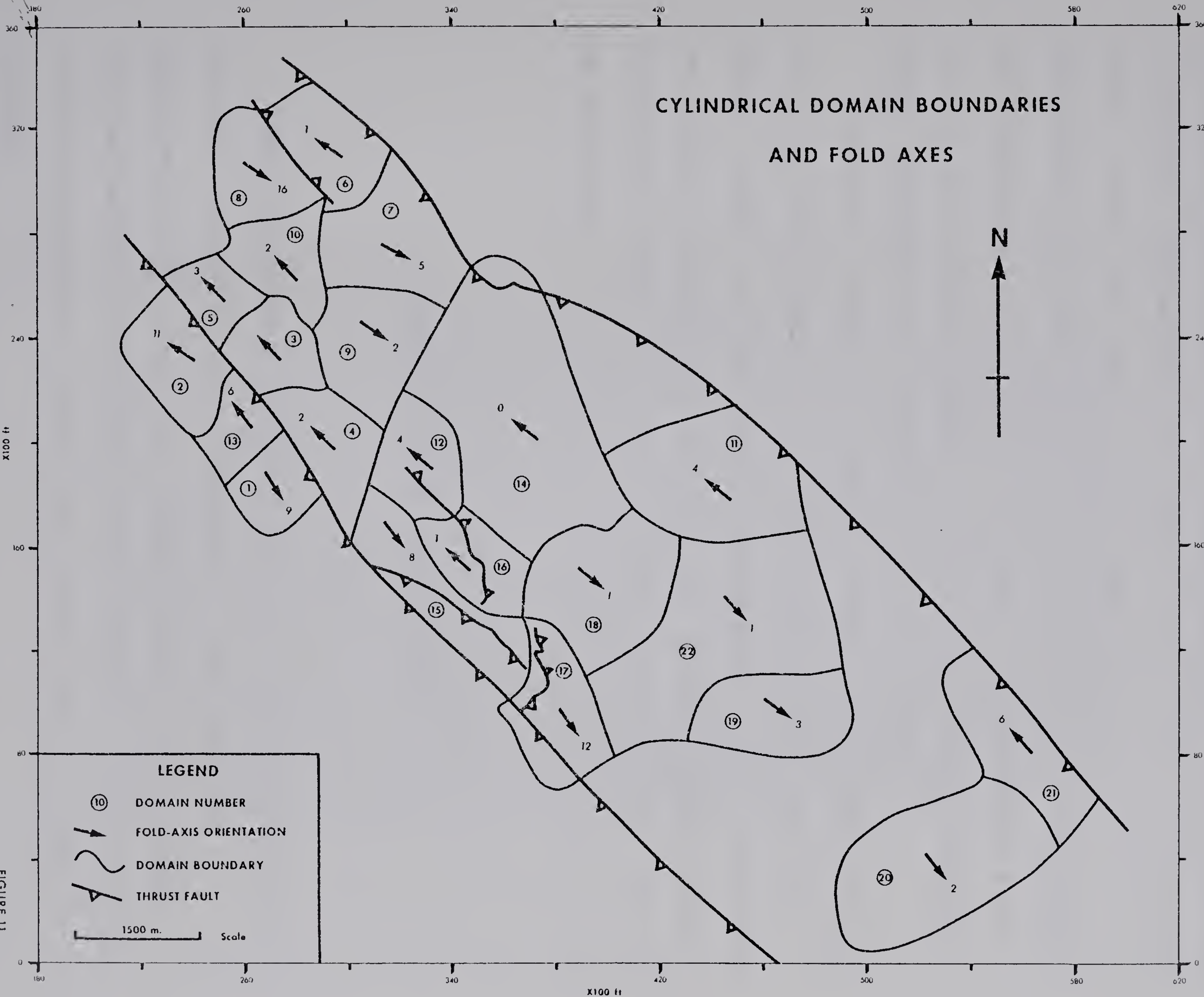

CYLINDRICAL DOMAIN BOUNDARIES
AND FOLD AXES
N
LEGEND
DOMAIN NUMBER
FOLD-AXIS ORIENTATION
DOMAIN BOUNDARY
THRUST FAULT
1500 m.
Scale
X100 ft
X100 ft

FIGURE 11

and cuts up section to the northeast at about 20°. It superimposes Nikanassin and Cadomin on Luscar strata and has an apparent displacement of about 2.5 km. Small sub-parallel thrust faults with displacements less than 10 m are particularly abundant in the basal 50 m of the thrust-sheet. Two macroscopic and several mesoscopic chevron folds with axial planes dipping steeply northeast and hinges plunging gently northwest were observed on Mount Hamell.

On Mount Hamell the plunge of folds in the thrust-sheet is to the northwest. In the floor of the Smoky River the plunge becomes southeastwards and steepens to 10°, bringing the Cadomin Formation in contact with Luscar strata across the Cowlick fault. On Grande Mountain the plunge is again to the northwest.

Syncline Hills Thrust-sheet

The northeastern limit of the study area is marked by the Syncline Hills Thrust, dipping to the southwest at approximately 50°. The fault, which brings Luscar strata onto the Kaskapau Formation in the footwall, is not a major thrust and cannot be traced along strike for any great distance.

Most of the Syncline Hills thrust-sheet is underlain by the Campbell Flats anticlinorium (Plate 1). The

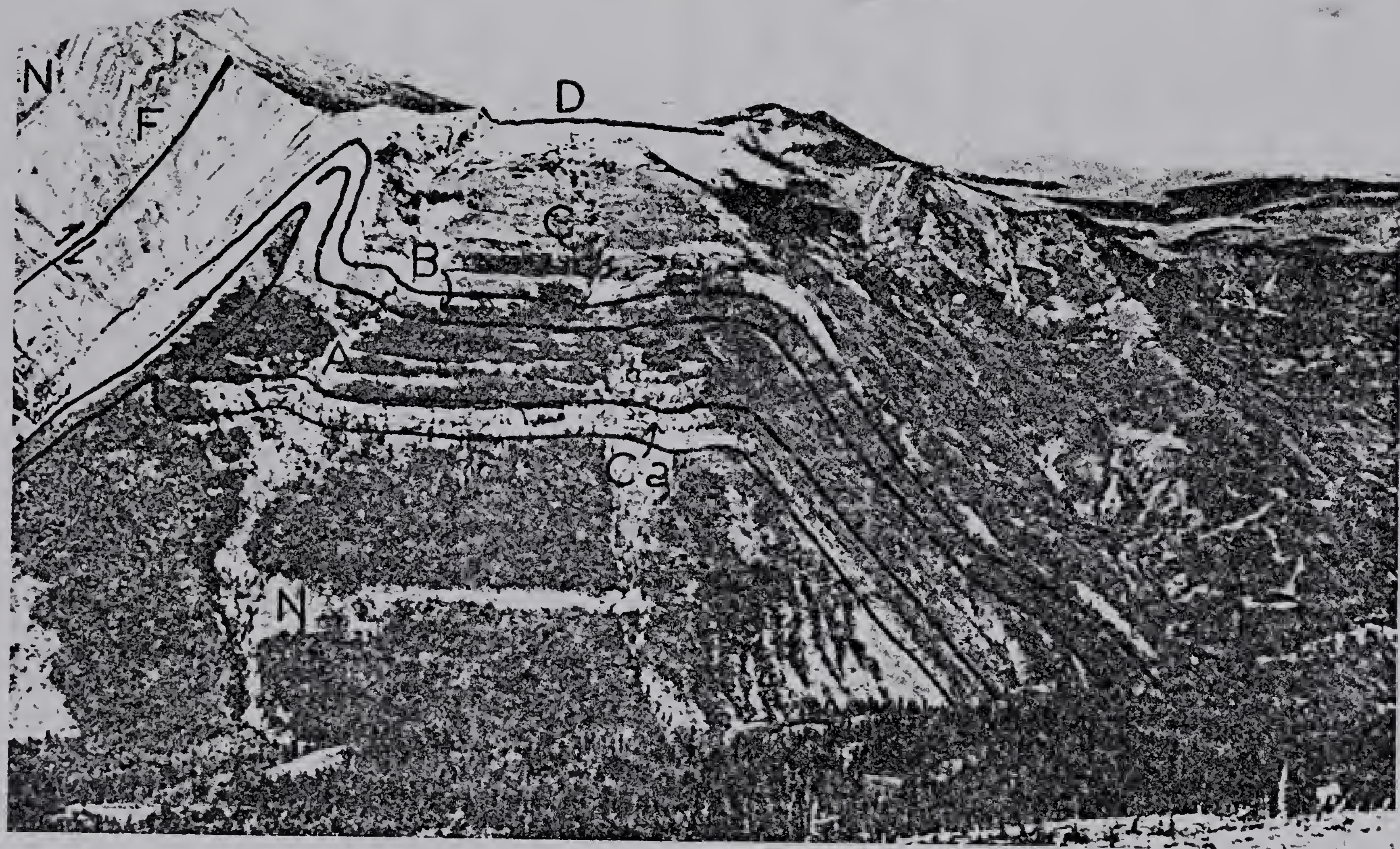
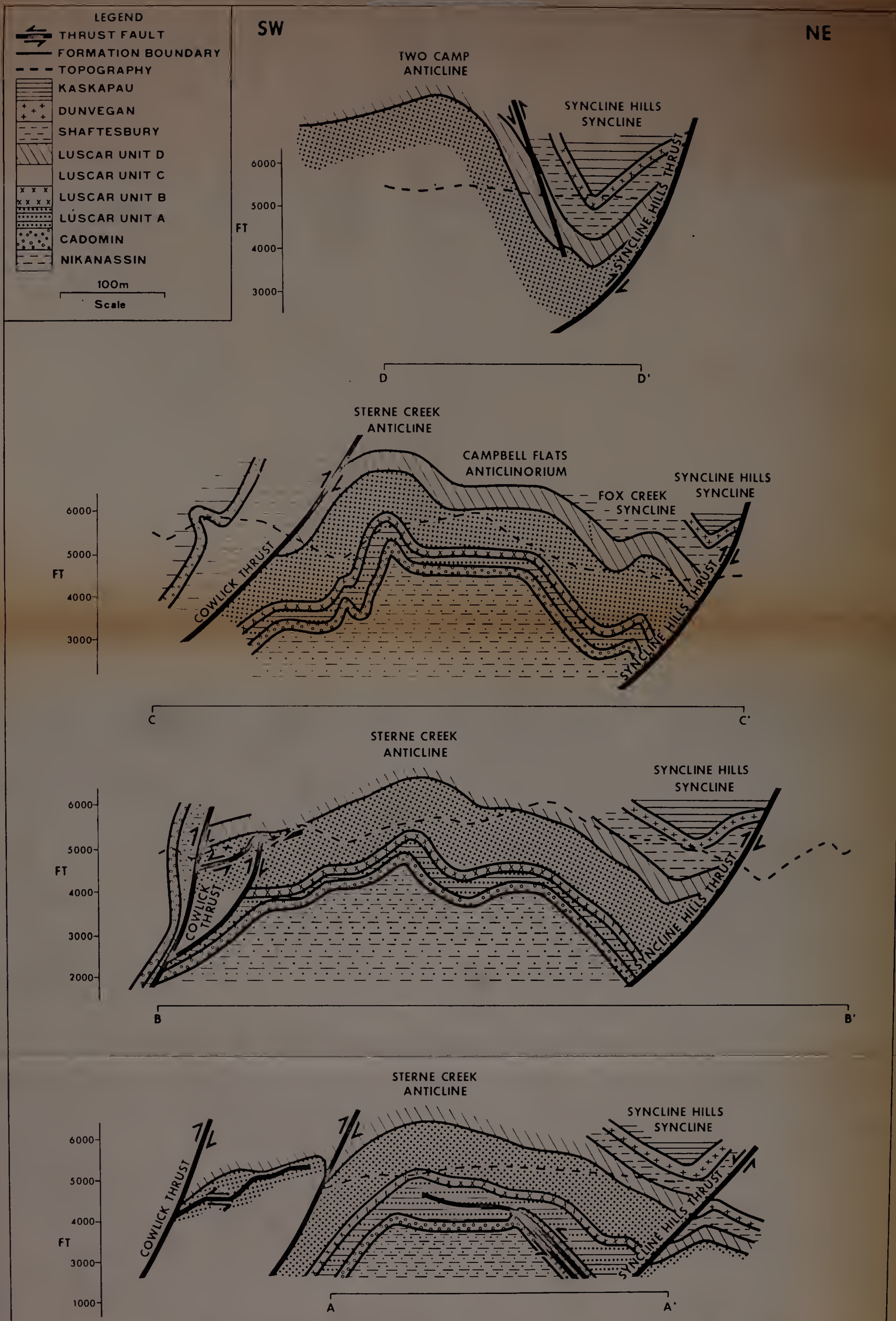


PLATE 1. Southeastern slope of Mount Hamell viewed from Grande Mountain; N-Nikanassin; Ca-Cadomin; A, B, C, D-Luscar units A, B, C, D respectively; F-Cowlick Thrust

anticlinorium exposes Nikanassin and Cadomin strata along the Smoky River, with Luscar strata forming the higher ground on Mount Hamell and Grande Mountain. The Shaftesbury, Dunvegan and Kaskapau Formations are confined to the higher ground on both sides of the river, and to the core of the Syncline Hills syncline which borders the Campbell Flats anticlinorium to the northeast (Fig. 12).

At the level of the Nikanassin and Cadomin Formations the Campbell Flats anticlinorium resembles a box-fold with a horizontal central limb. The Cadomin Formation in the fold which borders the central limb to the southwest, known as the Sterne Creek anticline, actually projects about 250 m above the level of the Cadomin in the central limb, forming an ear to the box-fold. Its northwesterly trending fold-axis is horizontal in domains 3 and 4 and gently plunging to the northwest in domain 5. There is a corresponding change in the orientation of the axial plane from 37° 54° to 46° 82° and in the value of the apical angle from 95° to 60° (axial plane orientations given as dip direction and dip, fold-axis orientations given as trend and plunge).

Two Camp anticline, the fold bordering the central limb of the anticlinorium to the northeast, is a simple chevron fold at the level of the Cadomin Formation, in domains 9 and 10. Towards the northwest in domain 8, within the Luscar Formation, the fold becomes more complex, forming a northeastern ear to the Campbell Flats anticlinorium. The southeasterly trending fold-axis is essentially horizontal



Composite downplunge projections along the indicated lines of section

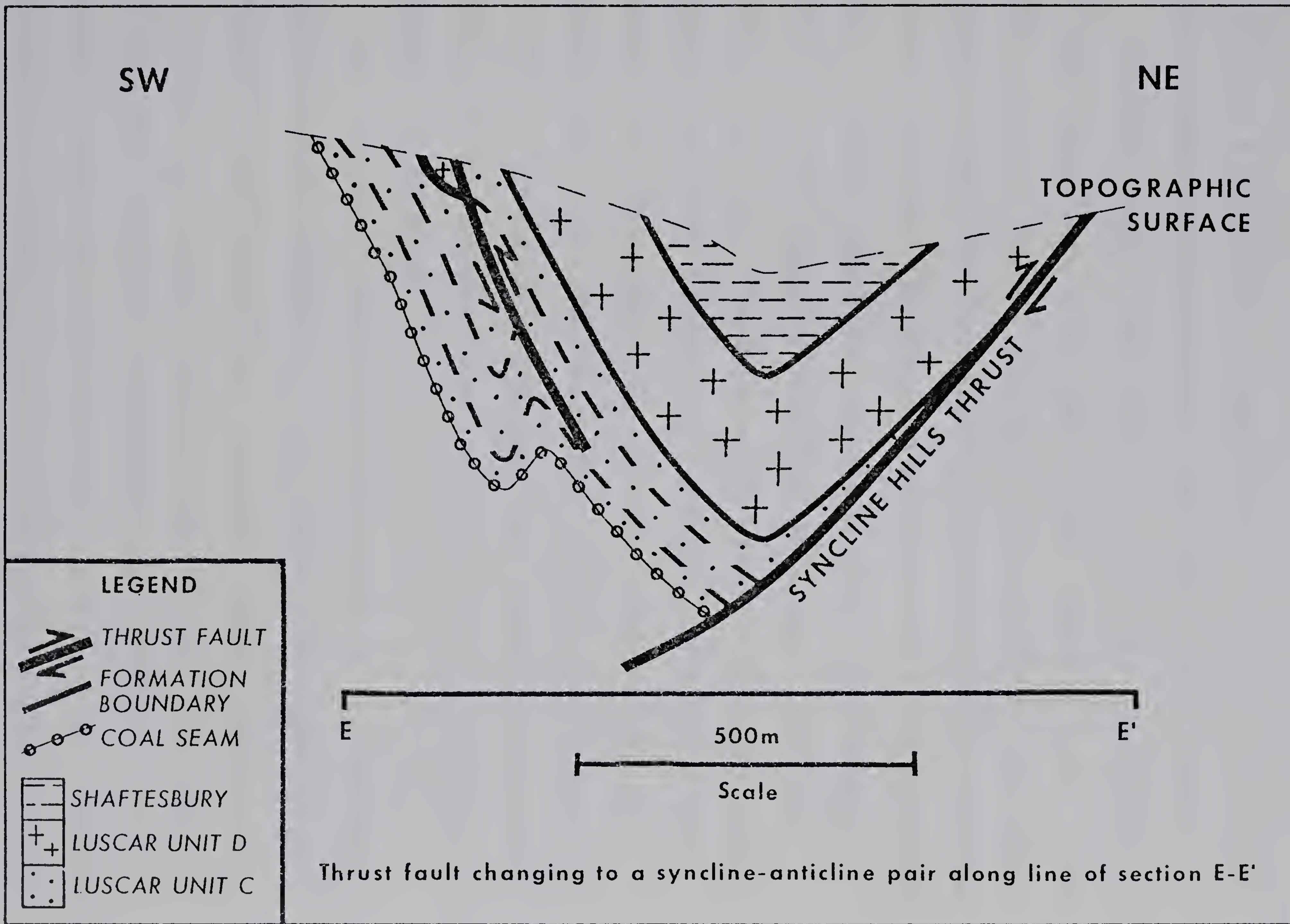
FIGURE 12

in domains 9 and 10 but steepens to 15° SE in domain 8, whereas the dip of the northwesterly striking axial surface changes from 60° SW in domains 9 and 10 to 75° SW in domain 8. There is a corresponding decrease in the apical angle, from 120° to 80°.

Fox Creek syncline and a small unnamed anticline lie to the northeast of Two Camp anticline. The fold-axes of these rounded chevron folds plunge to the southeast at 5° and the axial planes dip to the southwest at 75°. Along strike to the northwest the two folds are replaced by a steep, northeasterly dipping reverse fault (Fig. 13). In the hanging wall of the fault, the tight, chevron, Syncline Hills syncline, with an apical angle of 50°, plunges gently to the west-northwest with an almost vertical axial plane. Directly below the fold to the northeast is the Syncline Hills thrust.

The major box-fold so conspicuous on Mount Hamell, cannot be identified southeast of the Smoky River on Grande Mountain. However, Sterne Creek anticline and Syncline Hills syncline are easily located.

Sterne Creek anticline with a horizontal, southeasterly trending fold-axis has an axial plane orientation of 50° 78° and an apical angle of about 100°. The fold is no longer a simple structure, however, and in its southwestern limb contains both southwesterly and shallow northeasterly dipping thrusts which cut up section at low angles to the northeast and southwest, respectively. Southeast of the



Thrust fault changing to a syncline-anticline pair along line of section E-E'

FIGURE 13

crest of Grande Mountain, Sterne Creek anticline appears as an asymmetric chevron fold, disrupted on the southwest limb by a small thrust with a displacement of about 1 km that brings Cadomin and Nikanassin beds onto Luscar strata.

Between Sterne Creek anticline and the continuation of Fox Creek syncline, four small folds, which die out on the lower slopes of Grande Mountain, were observed. Two Camp anticline cannot be correlated across the river. Fox Creek syncline and the adjacent anticline also die out below the crest of Grande Mountain. All these folds have nearly horizontal southeasterly trending fold-axes and axial surfaces that dip southwest at about 70°. Syncline Hills syncline continues across the northern slopes of Grande Mountain as a more open fold with an apical angle of approximately 100 . The geographic extent and geometry of the folds on individual surfaces are displayed on structure contour and overburden maps produced for coal seams 3, 4 and 10 (Fig. 14,15,16,17,18,19).

The structure of the area southeast of Grande Mountain remains obscure because of poor exposure and the virtual absence of drill hole data. A quarry, beside highway 40, in the faulted and folded strata of the Cadomin Formation provided good artificial outcrops. The geometry of the folding is that of a box-fold with one ear on the northeast limb which is faulted by two northeasterly dipping thrusts with a combined displacement of about 250 m. The northwestern limb of the box-fold is a continuation of

Sterne Creek anticline, with the ear structure not evident.

Mesoscopic Structural Geology

Minor bedding-plane faults with almost no apparent displacement are common in the interbedded strata of the Luscar and Nikanassin Formations. The faults follow bedding for a distance, then cut up section for generally a meter or less and then resume a position parallel to another stratigraphic level. Larger faults with displacements of 1 to 10 m are common (dipping both to the southwest and northeast) and normally make an angle with bedding of 30 or less.

Most of the mesoscopic folding is congruent with the macroscopic folds although incongruent folds do occur adjacent to faults (Fig. 6). Tight chevron folds and numerous kink bands varying in width from 0.5 to 5 m are common. Insufficient data were collected on jointing and coal cleat to warrant comment.

Discussion

Abundant bedding plane slickensides perpendicular to

the fold-axes throughout much of the area indicate that the flexural slip mechanism of deformation was active. This mechanism, along with the narrow hinge zones, planar limbs and the discontinuity of the folds both along strike and vertically, suggest that kink folding on a macroscopic scale was the primary means of deformation (Faill, 1969, 1973). The sudden changes in orientation of many fold-axes and the limited geographic extent of the cylindrical domains (e.g. Two Camp anticline) are characteristic of kink folds. Numerous mesoscopic kink bands were also observed. The geometry of most of the folds in the area can be described in terms of large scale kink bands of various sizes and orientations (Fig. 20).

The steep Cowlick and Syncline Hills faults are probably rotated imbricate thrusts in the hanging wall of a major thrust, possibly the Mason thrust, which is the largest fault in the foothills north of the Athabasca River. This fault could also be acting as a zone of decollement between the Jurassic and the pre-Jurassic strata.

Three levels of disharmonic mesoscopic deformation are observable in the stratigraphic succession. Much of the deformation present in the Nikanassin Formation terminates near the base of the Cadomin Formation. The second level is bounded above by the thick shale horizon located 90 m above the base of the Luscar Formation. The third level, within which minor faulting predominates over folding, lies in the upper Luscar strata above the shale horizon. From the

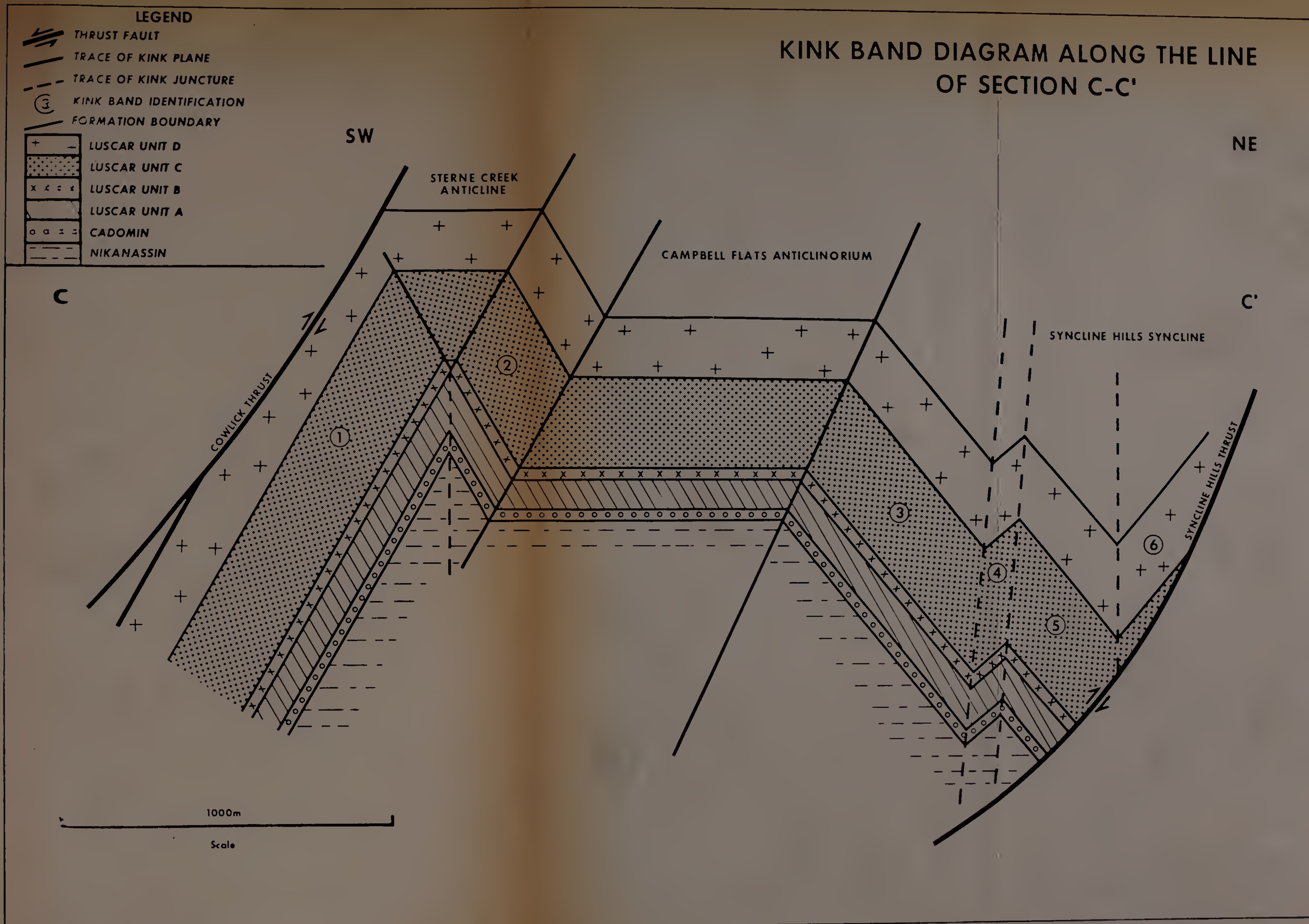

KINK BAND DIAGRAM ALONG THE LINE OF SECTION C-C'
LEGEND
THRUST FAULT
TRACE OF KINK PLANE
TRACE OF KINK JUNCTURE
KINK BAND IDENTIFICATION
FORMATION BOUNDARY
LUSCAR UNIT D
LUSCAR UNIT C
LUSCAR UNIT B
LUSCAR UNIT A
CADOMIN
NIKANASSIN
SW
NE
C
C'
STERNE CREEK ANTICLINE
CAMPBELL FLATS ANTICLINORIUM
SYNCLINE HILLS SYNCLINE
COWLICK THRUST
SYNCLINE HILLS THRUST
1
2
3
4
5
6
1000m
Scale

FIGURE 20

geological map (Fig. 4), many folds and faults can be seen to terminate or alter in configuration near these boundaries.

SUMMARY

This study has attempted to contribute to the understanding of the geology of the foothills of west-central Alberta and to provide some insight into the applications of some computer-based techniques that may be used during exploration for coal seams in structurally complex areas. Specifically, this thesis accomplishes the aims outlined in Chapter 1, namely: (1) to determine the stratigraphy of the Luscar Formation; (2) to describe the structure of the Luscar and adjacent formations in the vicinity of Mount Hamell and Grande Mountain; (3) to develop a computer-based structure contouring procedure that utilizes orientation, positional and stratigraphic data; and (4) to demonstrate the usefulness of some computer-based techniques in determining and analysing the structural geology of coal measures. The structure contouring procedure is particularly useful during preliminary exploration for coal to assess potential mining areas and to prepare structure contour and overburden maps of coal seams without the need for extensive drilling.

Additional detailed studies such as this, through cooperation between the university, industry and government research agencies, are required to gain a fuller

understanding of the geology of the Foothills of the Western Canadian Rocky Mountains and to develop new and refine existing computer-based procedures helpful in determining and analysing their structure.

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APPENDIX 1.

The format and contents of the file DATA are as follows:

LINE 1

Column	Description
1	Numeric code specifying form of orientation data: 1= trend and plunge 2= dip-direction and dip 3= strike (right-handed) and dip
2-41	Title.

SECOND TO SECOND LAST LINES

Column	Description
1-4	Identification number.
9-10	Binary code of which the first digit identifies formation and the second stratigraphic position within the formation: 90= Kaskapau Formation 80= Dunvegan Formation 70= Shaftesbury Formation 40= Luscar Formation (undivided) 57= upper 100-125 m of the formation 56= 25 m interbedded medium grained and pebbly sandstones 55= 35 m of sandy and shaly strata 54= 18 m lithic sandstone (upper sandstone) 53= 40 m of interbedded shale and sandstone 52= 20 m lithic sandstone (lower sandstone) 51= Coal seams 10, 8, 7, 6 and related strata. 50= 15 m of shale 49= Coal seam 4, "Super 4" sandstone and related strata 48= 15 m of shale and sandstone 47= Coal seam 3, "Salt and Pepper" sandstone and related strata 46= 25 m of mudstone, siltstone and sandstone. 45= 31 m of mudstone 44= Coal seams 2, 1.5 and related strata. 43= Coal seam X and related strata. 42= Coal seam 1 and overlying sandstone 41= lower 20 m of the formation with coal W

30= Cadomin Formation (undivided)
  33= upper conglomerate
  32= middle sandstone
  31= lower conglomerate
20= Nikanassin Formation

11-14	Distance in feet of exposed horizon above base of formation to which it belongs.
15-29	X (easterly), Y (northerly) and Z (elevation) coordinates in feet.
30	Station position reliability indicator found by dividing estimated possible error in feet by 10.
31-38	Presence of additional information recorded elsewhere was indicated by a 1=yes or 0=no entry in these columns. 31= bedding plane linears 32= mesoscopic folds 33= faults 34= joints 35= lithology 36= fossils 37= general observations including sketches 38= photos
39-79	Bedding orientations recorded as six 6-digit entries of dip-direction and dip with a space between each entry. Dip-direction, the azimuth of the direction normal to the strike in which the strata young, can range from 0 to 400 grads. Dip, the angle through which the strata have apparently been rotated, can range from 0 to 200 grads, being greater than 100 grads in the case of overturned beds.
80	Presence of additional bedding orientations recorded elsewhere was indicated by a 1=yes or 0=no entry in this column.

LAST LINE

Column	Description
1	/

APPENDIX 2.

The format and contents of the file BOREHOLE are as follows:

FIRST TO LAST LINES

Column	Description
1	Alphanumeric code designating: 5= topographic surface 1-4= coal seams 1-4 (tops) 6-9= coal seams 6-8 and 10 (tops) D= Cadomin Formation (top) Z= fault
2-16	Coordinates of intersection of above surface and borehole as in DATA.
71-74	Identification of which digits 1 and 2 indicate year of drilling and 3 and 4 identify borehole in McIntyre Mines' records.
80	1 (see program DRAW).

APPENDIX 3.

Listings of computer programs written for data processing with appropriate inputs and outputs.

DELET

input   5=DATA

output   6=-DATA1

```
C ---  TO CONVERT GRADS TO DEGREES AND ASSIGN A LETTER CODE
C ---  TO STRATIGRAPHIC HORIZONS
      DIMENSION X(50)
      INTEGER FM,DB,X
      INTEGER CODE(26)/'A','B','C','D','E','F','G','H','I','J','K',
     *'L','M','N','O','P','Q','R','S','T','U','V','W','X','Y','Z'/
      K=0
C ---  READ IN RAW DATA
    1 READ(5,10,END=3)NO,FM,DB,IX,IY,IZ,M1,M2,M3,M4,M5,M6,M7,M8,M9,
     *(X(J),J=1,12),MO
C ---  CHANGE GRADS TO DEGREES
      DO 2 J=1,12
      X(J)=X(J)*0.9+0.5
    2 CONTINUE
C ---  ASSIGN THE LETTER CODE
      IF(FM .EQ. 0) GO TO 6
      IF(FM .EQ. N) GO TO 5
      K=K+1
      N=FM
C ---  WRITE THE NEW DATA
    5 WRITE(6,11)CODE(K),NO,FM,DB,IX,IY,IZ,M1,M2,M3,M4,M5,M6,M7,M8,
     *M9,(X(J),J=1,12),MO
      GO TO 7
    6 WRITE(6,12)NO,FM,DB,IX,IY,IZ,M1,M2,M3,M4,M5,M6,M7,M8,M9,
     *(X(J),J=1,12),MO
    7 CONTINUE
      GO TO 1
   10 FORMAT(I4,4X,I2,I4,3I5,9I1,2I3,5(1X,2I3),I1)
   11 FORMAT(A1,I4,3X,I2,I4,3I5,9I1,2I3,5(1X,2I3),I1)
   12 FORMAT(1X,I4,3X,I2,I4,3I5,9I1,2I3,5(1X,2I3),I1)
    3 STOP
      END
ND OF FILE
```

SORT

input 5=-DATA1

output 6=-DATA2

```
      C --- TO SORT DATA AS INPUT FOR MEANS.S ---
            DIMENSION X(50)
            INTEGER A,B,C,X
            WRITE(6,30)
            DO 1 I=1,800
            READ(5,10,END=3) K,A,B,C,(X(J),J=1,12)
            WRITE(6,20) K,A,B,C,(X(J),J=1,12)
          1 CONTINUE
         10 FORMAT(A1,13X,3I5,9X,2I3,5(1X,2I3))
         20 FORMAT(A1,3I5,6(1X,2I3))
         30 FORMAT('2',3X,'GRANDE CACHE')
         40 FORMAT('/')
          3 CONTINUE
            WRITE(6,40)
            STOP
            END
END OF FILE
```

RESORT

inputs   4=-DATA1
          5=-MEAN (from MEANS)
          7=-KV (from MEANS)

output   6=MEANN

```
C --- TO ARRANGE DATA AS INPUT INTO NUMERICAL PROGRAMS ---
      INTEGER X,Y,Z,D,P,N,F
      WRITE(6,10)
      DO 1 I=1,800
      READ(5,20,END=2) K,X,Y,Z,D,F
      READ(4,30) N,P,LEN,M1,M2,M3,M4,M5,M6,M7,M8,M9,M10
      READ(7,60) NN,CC,L1,L2
      WRITE(6,40) K,X,Y,Z,D,P,NN,CC,L1,L2,M10,M1,M2,M3,
     *M4,M5,M6,M7,M8,M9,LEN,N,F
    1 CONTINUE

   10 FORMAT('2',3X,'GRANDE CACHE')
   20 FORMAT(A1,3I5,1X,2I3)
   30 FORMAT(I4,4X,I2,I4,15X,9I1,41X,I1)
   40 FORMAT(A1,3I5,1X,2I3,2X,I1,2X,F6.2,2X,2I3,2X,I1,
     *2X,I1,2X,3I1,2X,I4,4X,I4,2X,I2)
   60 FORMAT(26X,I1,2X,F6.2,1X,I3,1X,I3)
   50 FORMAT('/')
    2 CONTINUE
      WRITE(6,50)
      STOP
      END
END OF FILE
```

SELECT

inputs 4=MEANN
5=OUTNUM (outcrop numbers of data stations to be retrieved)

output 6=DOMX (domain file)

```
C----- TO SELECT DATA STATIONS FROM THE FILE MEANN ----
C----- AND TO PLACE THEM IN A FILE DOMX FOR DOMAIN -----
C----- ANALYSIS . THE STATION NUMBERS ARE INPUT INTO ---
C----- SELECT IN A FILE -DOMX.                      -----
      DIMENSION N(150)
      INTEGER X,Y,Z,DO,DI,L,L1,M,C,N,OB,DO1,DI1
      REAL CP
      READ(5,13) B,C
      WRITE(6,13) B,C
      DO 1 J=2,150
      READ(5,10,END=2)N(J)
    5 READ(4,11,END=2)K,X,Y,Z,DO,DI,NN,CC,L,L1,M1,M2,M3,M4,M5,
     *M6,M7,M8,M9,M10,B,C,OB
      IF(N(J)-C)4,6,4
    6 WRITE(6,11)K,X,Y,Z,DO,DI,NN,CC,L,L1,M1,M2,M3,M4,M5,
     *M6,M7,M8,M9,M10,B,C,OB
      GO TO 1
    4 CONTINUE
      GO TO 5
    1 CONTINUE
    2 CONTINUE
      WRITE(6,15)
   10 FORMAT(I4)
   11 FORMAT(A1,3I5,1X,2I3,2X,I1,2X,F8.2,2X,2I3,2X,I1,2X,I1,
     *2X,8I1,2X,I4,4X,I4,2X,I2)
   13 FORMAT(I1,7HDOMAIN,I3)
   15 FORMAT('/')
      STOP
      END
END OF FILE
```

SLICKS

input 5=PITCH (file containing orientation of planar surface and pitches of slickenside striae)

output 6=SLICKENS

```
C ---  SLICKS IS DESIGNED TO FIND TREND AND PLUNGE OF
C ---   LINEARS MEASURED AS A CLOCKWISE PITCH ON A PLANE
         INTEGER DD,DI,PIT,NO,X,Y,Z,PLUN,TREN
         DTR=1.754329E-2
         RND=90.0*DTR
         READ(5,10)NO,X,Y,Z
         READ(5,11)DD,DI
         WRITE(6,12)NO,X,Y,Z
         WRITE(6,13)
         XDD=DD*DTR
         XDI=DI*DTR
         DO 1 I=1,50
         READ(5,14,END=2)PIT
         XPIT=PIT*DTR
         XP=ASIN(COS(RND-XPIT)*COS(RND-XDI))
         XC=RND-ASIN(TAN(XP)*TAN(RND-XDI))
         IF(PIT-90)4,5,5
       4 XT=XDD-XC
         GO TO 6
       5 XT=XDD+XC
       6 CONTINUE
         TREN=XT/DTR+0.5
         IF(TREN .LT. 0)TREN=TREN+360
         IF(TREN .GT. 360)TREN=TREN-360
         PLUN=XP/DTR+0.5
         WRITE(6,11)TREN,PLUN
       1 CONTINUE
       2 CONTINUE
         WRITE(6,15)
      10 FORMAT(6X,I3,1X,3I5)
      11 FORMAT(2I3)
      12 FORMAT('STATION',1X,I3,1X,3I5)
      13 FORMAT('TYPE=1')
      14 FORMAT(I3)
      15 FORMAT('END')
         STOP
         END
END OF FILE
```

APPENDIX 4.

The format and contents of the file MEANN are as follows:

LINE 1

Same as for DATA.

SECOND TO SECOND LAST LINES

Column	Description
1	Alphanumeric code designating stratigraphic position, coal seam number, etc: Y= Kaskapau Formation X= Dunvegan Formation W= Shaftesbury Formation E= Luscar Formation, interval unknown F-V= Luscar Formation, intervals 41-57 1-4= Luscar Formation, coal seams 1-4 6-9= Luscar Formation, coal seams 6-8 and 10 B-D= Cadomin Formation, intervals 31-33 A= Nikanassin Formation Z= Fault 5= surface coordinates of a borehole
2-16	Station coordinates as in DATA.
18-23	Mean bedding orientation.
26	Number of repetitive bedding orientations.
29-36	Concentration parameter.
39-44	First bedding orientation measured at outcrop.
47	Same as column 80 in DATA.
50	Same as column 30 in DATA.
53-60	Same as columns 31-38 in DATA.
63-66	Same as columns 11-14 in DATA.
71-74	Same as columns 1-4 in DATA.
77-78	Same as columns 9-10 in DATA.

LAST LINE

Same as last line in DATA.

APPENDIX 5.

Listing of the program DRAW with the appropriate run commands.

```
inputs   4=*SOURCE*
               xmin, ymin = coordinates of lower left-hand
               corner of map
               xmax, ymax = coordinates of upper right-hand
               corner of map
               scale = scale in feet per inch on map
               ht = height of characters in tenths of an inch
               dtic = distance in inches between distance
               markers on the map boundaries
               ocnum = 0, outcrop numbers not plotted, or 1,
               outcrop numbers plotted
         5=MAPFILE (input file to be plotted)

output   9=plotted map
```

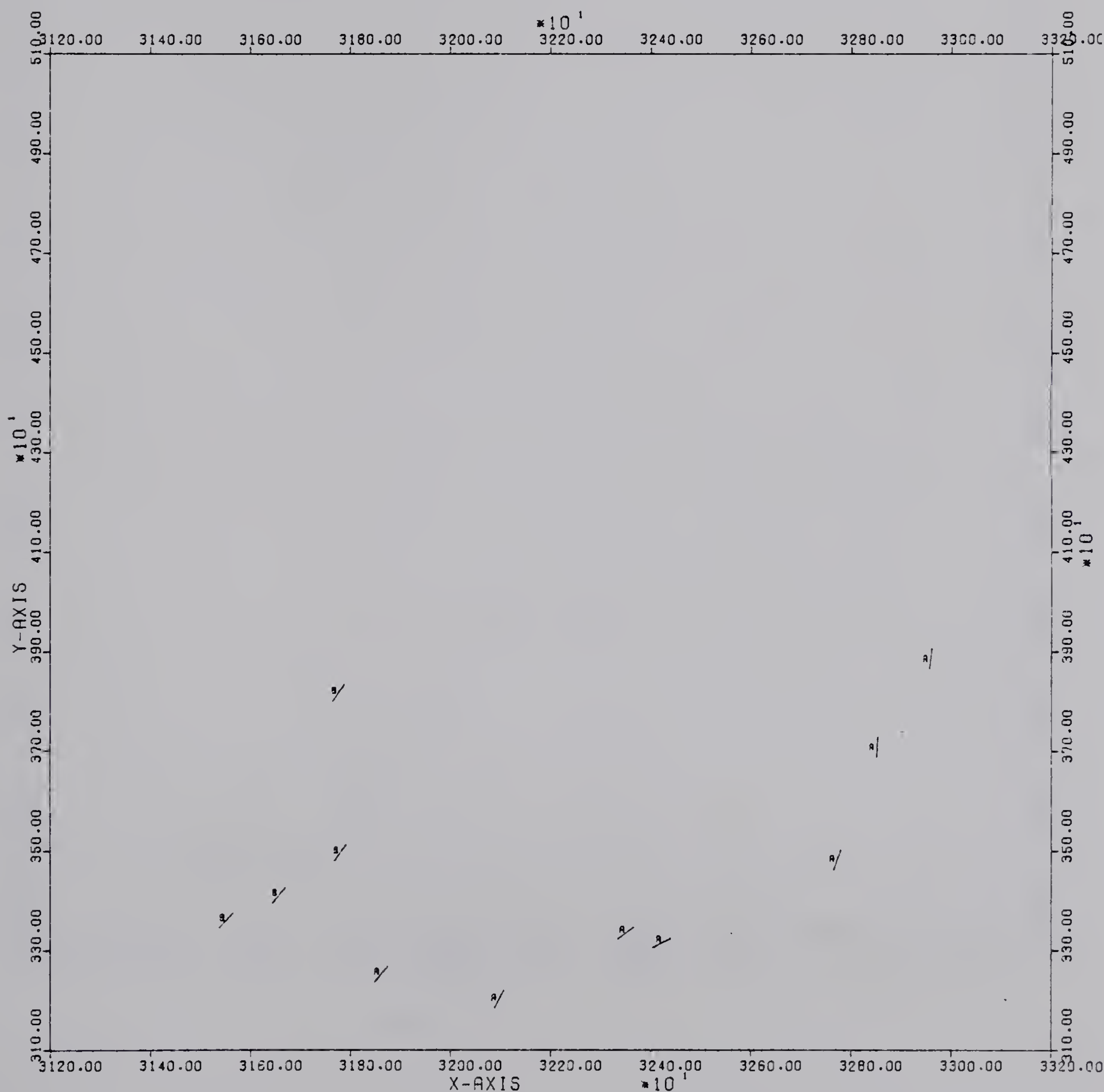
```
C*********DRAW IS DESIGNED TO PLOT DIP-DIRECTION AND DIP
C*********SYMBOLS ON A MAP ALONG WITH BOUNDARIES.
      INTEGER X,Y,XB,YB,IDENT
      REAL ET,X3,Y3,DD,DI,N,BX,BY,OCNUM
      CALL PLOTS
      CALL XLIMIT(110.0)
      READ(4,11) XMIN,YMIN,XMAX,YMAX,SCALE,ET,DTIC,OCNUM
      XLEN=(XMAX-XMIN)/SCALE
      YLEN=(YMAX-YMIN)/SCALE
      XBOUND=XLEN+1.0
      YBOUND=YLEN+0.5
      XMIN1=XMIN/100
      YMIN1=YMIN/100
      SCALE1=SCALE/100
C*********  DRAW BOUNDARIES  *****
 1000 CALL AXZER(2.0,1,-1)
      CALL AXIS2(1.0,0.5,' ',-1,XLEN,0.0,XMIN1,SCALE1,DTIC)
      CALL AXIS2(XBOUND,0.5,' ',-1,YLEN,90.0,YMIN1,SCALE1,DTIC)
      CALL AXIS2(1.0,0.5,' ',1,YLEN,90.0,YMIN1,SCALE1,DTIC)
      CALL AXIS2(1.0,YBOUND,' ',1,XLEN,0.0,XMIN1,SCALE1,DTIC)
C*********  READ ORIENTATIONS AND PLOT SYMBOLS  *****
    5 READ(5,10,END=2) X,Y,DD,DI,N,IDENT
      X3=X
      Y3=Y
      X3=(X3-(XMIN-SCALE))/SCALE
      Y3=(Y3-(YMIN-SCALE*0.5))/SCALE
      IF(X3 .LE. 1.) GO TO 1
      IF(X3 .GE. XBOUND) GO TO 1
      IF(Y3 .LE. .5) GO TO 1
      IF(Y3 .GE. YBOUND) GO TO 1
C*********DETERMINE IF STATION TO BE PLOTTED IS AN OUTCROP,
C*********BOREHOLE,FOLD-AXIS OR SLICKENSIDE
      IF(IDENT-1)300,400,500
  300 CALL DRAW(X3,Y3,N,ET,DD,DI,OCNUM)
      GO TO 51
  400 CALL SYMBOL(X3,Y3,ET,010,0.0,-1)
      GO TO 51
  500 CALL MESO(X3,Y3,DD,DI,ET,IDENT)
   51 CONTINUE
    1 CONTINUE
      GO TO 5
    2 CALL PLOT(0.,0.,999)
   10 FORMAT(1X,I5,I5,6X,F3.0,F3.0,47X,F4.0,5X,I1)
   11 FORMAT(8F6.1)
      STOP
      END
C****************  SUBROUTINE DRAW  ****************
      SUBROUTINE DRAW(X,Y,N,ET,DD,DI,OCNUM)
      REAL N
      REAL DD,DI,DDD,Z,W,V
      IF(DI .EQ. 0.0)GO TO 50
      REAL X,Y,S,ET,K,KK,P,Q,T
C********* CHECK IF BEDS OVERTURNED, IF SO ADD 180 TO DIP-DIRECTION
      IF(DI .LE. 90.) GO TO 15
      DDD=DD+180.
      IF(DDD .LE. 360.) GO TO 3
      DDD=DDD-360.
      W=ABS(DDD-450.)
      GO TO 6
    3 W=ABS(DDD-450.)
```

```
    6 G=W+90.
      H=W+270.
      R=HT/4.
      DD=DDD
C********  CONVERT DEGREES TO RADIANS  ****
   15 Z=DD*1.745329E-2
      U=(DD+180.)*1.745329E-2
      V=(DD+90.)*1.745329E-2
      K=(DD-90.)*1.745329E-2
      IF(DI .LE. 90.) GO TO 20
C******** COORDINATE CALCS. FOR OVERTURNED CIRCLE SYMBOL
C******** AND ITS PLOTTING
      X1=X+SIN(U)*(HT*.33)
      Y1=Y+COS(U)*(HT*.33)
      X2=X+SIN(V)*(HT*.5)
      Y2=Y+COS(V)*(HT*.5)
      X3=X2+SIN(U)*(HT*.33)
      Y3=Y2+COS(U)*(HT*.33)
      CALL PLOT(X,Y,3)
      CALL PLOT(X1,Y1,2)
      CALL CIRCLE(X1,Y1,G,H,R,R,0.0)
      CALL PLOT(X3,Y3,3)
      CALL PLOT(X2,Y2,2)
      DI=180.-DI
C********  DETERMINE COORDINATES FOR SYMBOL, DIP AND
C******** OUTCROP NUMBER
   20 E=X+SIN(Z)*(HT*.66)
      F=Y+COS(Z)*(HT*.66)
      A=X+SIN(V)*HT
      B=Y+COS(V)*HT
      C=X+SIN(K)*HT
      D=Y+COS(K)*HT
      IF(Z .GT. 2.3561942 .AND. Z .LT. 3.9269903) GO TO 101
      IF(Z .GE. 3.9269903 .AND. Z .LT. 5.4977864) GO TO 102
      E1=E+SIN(Z)*(HT*1.0)
      F1=F+COS(Z)*(HT*1.0)
      GO TO 103
  101 E1=E+SIN(Z)*(HT*2.2)
      F1=F+COS(Z)*(HT*2.2)
      GO TO 103
  102 E1=E+SIN(Z)*(HT*2.2)
      F1=F+COS(Z)*(HT*2.2)
  103 CONTINUE
      IF(Z-5.235987)202,205,205
  202 IF(Z-2.7925264)204,203,203
  203 XX=1.0
      GO TO 250
  204 IF(Z-0.5235987)205,221,221
  205 XX=2.0
      GO TO 250
  221 IF(N-100.)231,234,234
  231 IF(N-10.)232,233,233
  232 XX=2.0
      GO TO 250
  233 XX=3.0
      GO TO 250
  234 XX=4.0
  250 CONTINUE
      TX=X+SIN(U)*(HT*XX)
      TY=Y+COS(U)*(HT*XX)
```

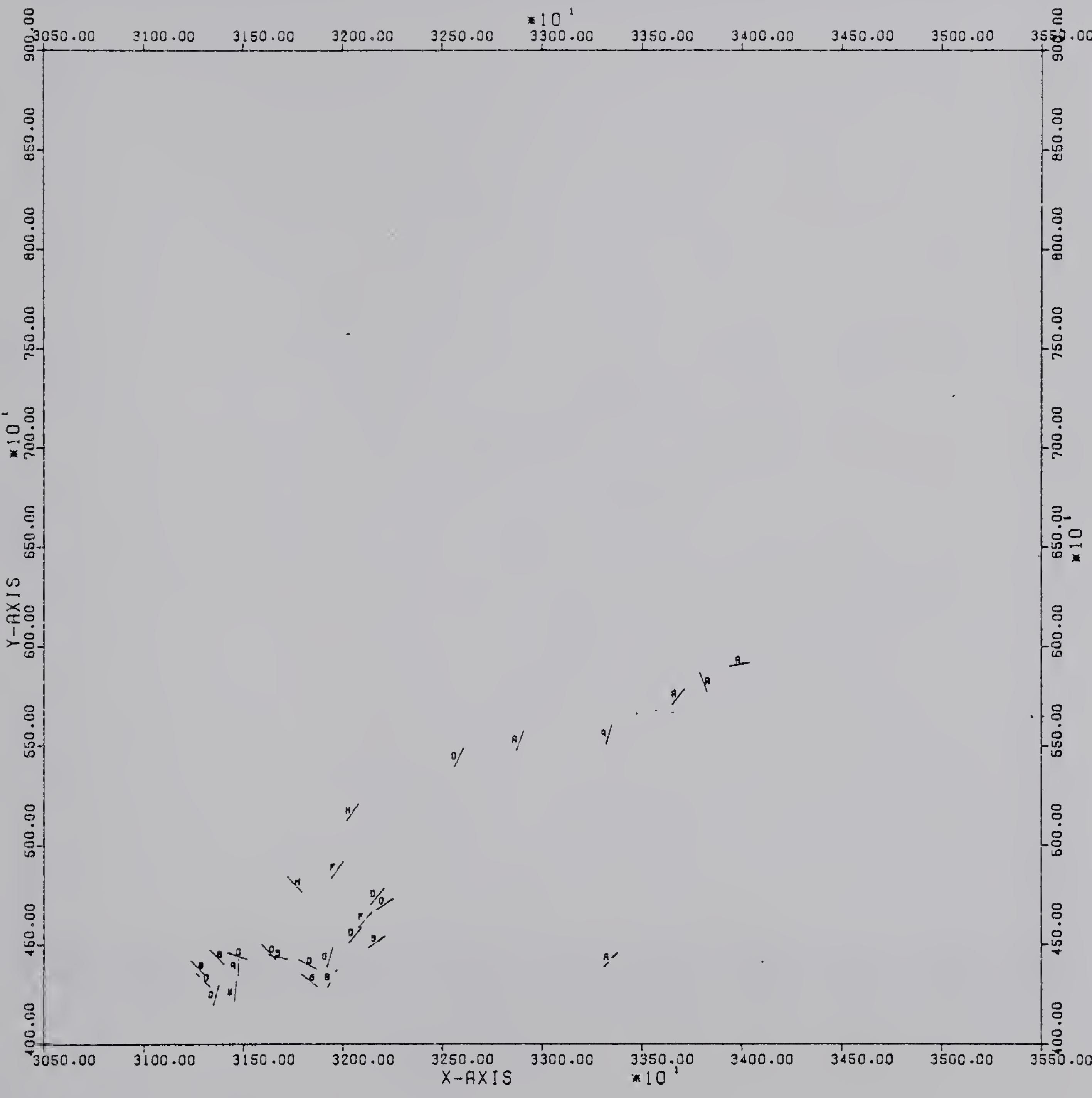
```
C*********  PLOT SYMBOL  ****
      CALL PLOT(E,F,3)
      CALL PLOT(X,Y,2)
      CALL PLOT(A,B,3)
      CALL PLOT(C,D,2)
      CALL NUMBER(E1,F1,HT,DL,0.0,-1)
      IF(OCNUM .EQ. 0.0)GO TO 30
      CALL NUMBER(TX,TY,HT,N,0.0,-1)
      GO TO 30
   50 CALL SYMBOL(X,Y,2*HT,003,0.0,-1)
   30 RETURN
      END
C*********  SUBROUTINE MESO  ****
C*********  TO PLOT TREND AND PLUNGE OF SLICKENSIDES AND
C*********  MESOSCOPIC FOLD AXES
      SUBROUTINE MESO(X,Y,TR,PL,HT,IDENT)
      REAL X,Y,TR,PL,HT
      INTEGER IDENT
      TR=ABS(TR-450.)
      TT=TR*1.745329E-2
      BA=TT+(30*1.745329E-2)
      CA=TT-(30*1.745329E-2)
      IF(IDENT-2)600,600,700
C*********  CALCULATE SLICKENSIDE SYMBOL  ****
  600 E=X+SIN(TT)*(HT*3.)
      F=Y+COS(TT)*(HT*3.)
      E1=X+SIN(TT)*(HT*5.)
      F1=Y+COS(TT)*(HT*5.)
      E2=X+SIN(TT)*(HT*6.5)
      F2=Y+COS(TT)*(HT*6.5)
      BAX=E1-SIN(BA)*HT
      BAY=F1-COS(BA)*HT
      CAX=E1-SIN(CA)*HT
      CAY=F1-COS(CA)*HT
      GO TO 800
C*********  CALCULATE FOLD AXIS SYMBOL  ****
  700 E=X+SIN(TT)*(HT*3.)
      F=Y+COS(TT)*(HT*3.)
      E1=X+SIN(TT)*(HT*8.)
      F1=Y+COS(TT)*(HT*8.)
      E2=X+SIN(TT)*(HT*9.5)
      F2=Y+COS(TT)*(HT*9.5)
      BAX=E1-SIN(BA)*(HT*1.5)
      BAY=F1-COS(BA)*(HT*1.5)
      CAX=E1-SIN(CA)*(HT*1.5)
      CAY=F1-COS(CA)*(HT*1.5)
C*********  PLOT SYMBOLS  ****
  800 CALL PLOT(E,F,3)
      CALL PLOT(E1,F1,2)
      CALL PLOT(BAX,BAY,2)
      CALL PLOT(CAX,CAY,3)
      CALL PLOT(E1,F1,2)
      CALL NUMBER(E2,F2,HT,PL,0.0,-1)
      RETURN
      END
END OF FILE
```

APPENDIX 6.

Profile plots of the down-plunge projections of the twenty-two structural domains delineated for the study area.

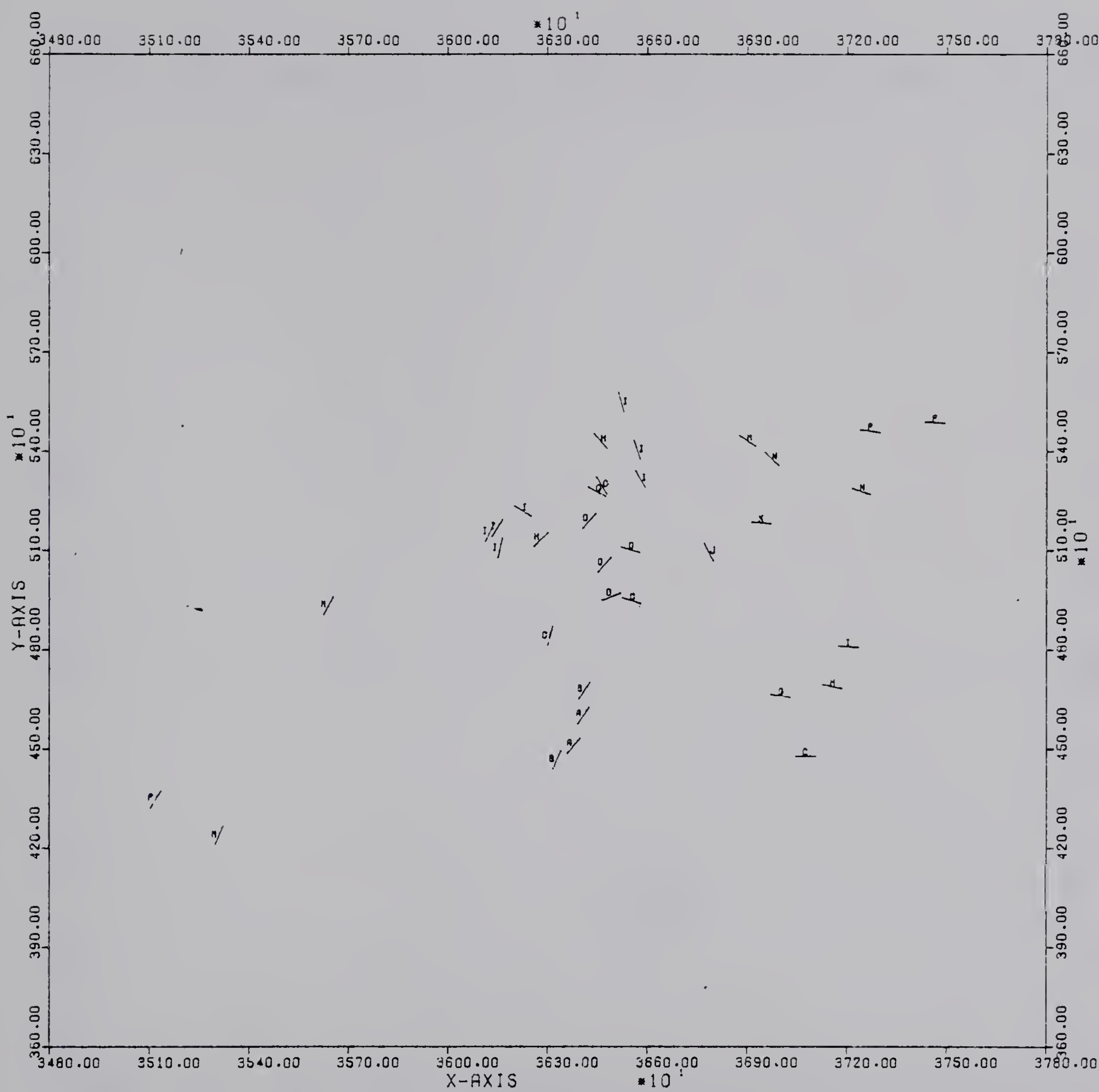


DOMAIN 1

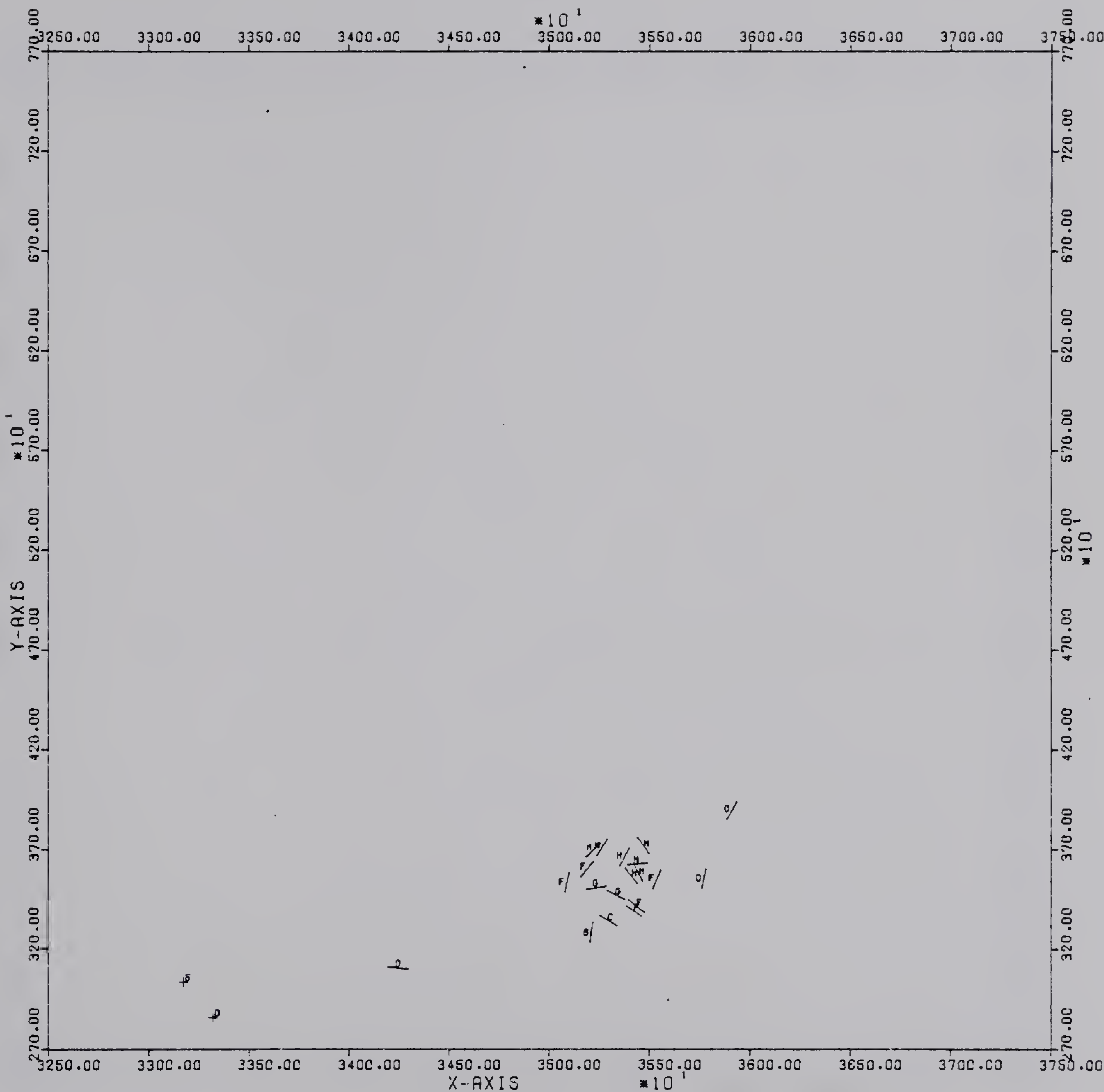


*10¹
3050.00
3100.00
3150.00
3200.00
3250.00
3300.00
3350.00
3400.00
3450.00
3500.00
3550.00
900.00
850.00
800.00
750.00
700.00
650.00
600.00
550.00
500.00
450.00
400.00
Y-AXIS
X-AXIS

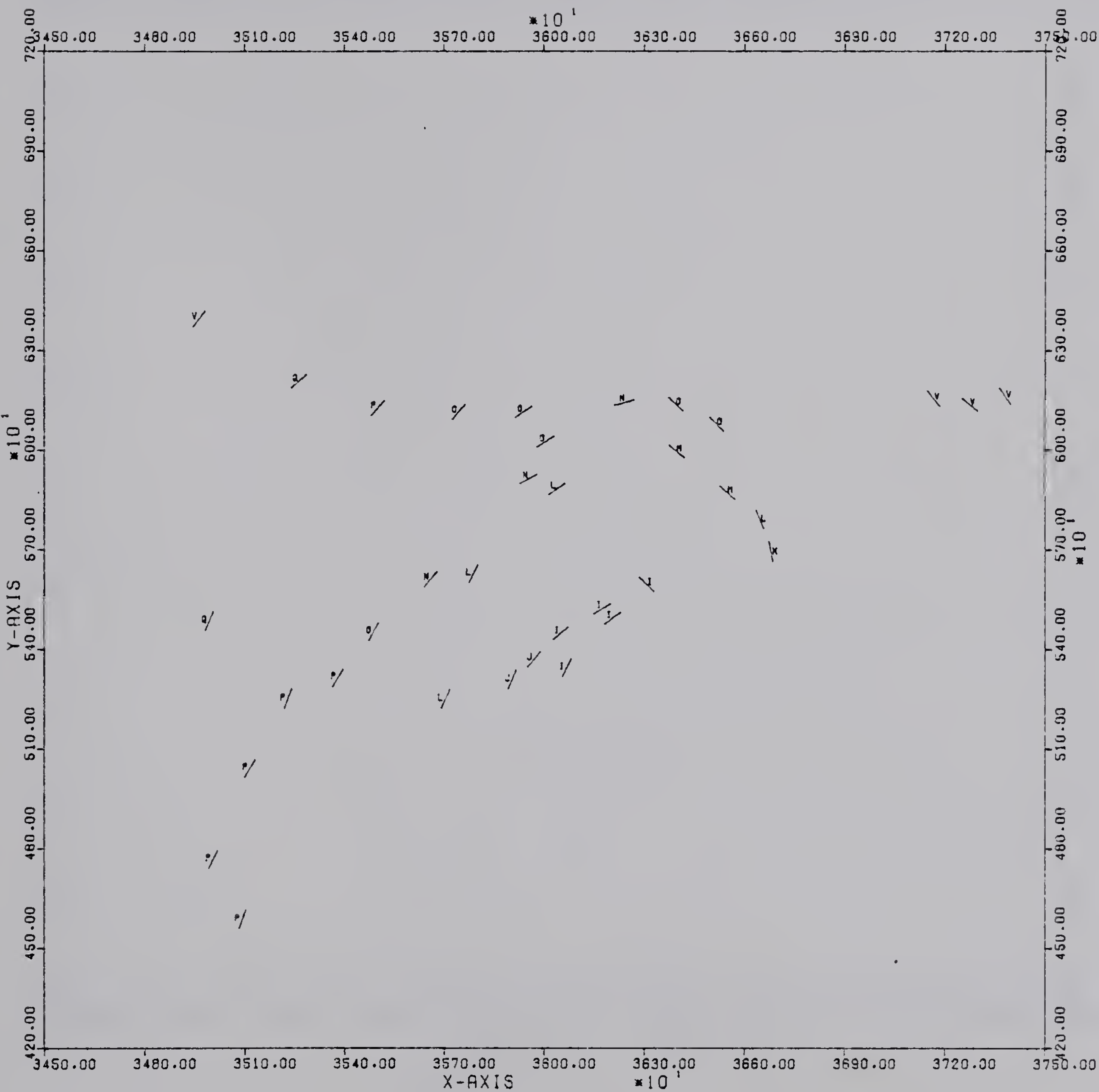
DOMAIN 2


*10¹
3480.00
3510.00
3540.00
3570.00
3600.00
3630.00
3660.00
3690.00
3720.00
3750.00
3780.00
660.00
630.00
600.00
570.00
540.00
510.00
480.00
450.00
420.00
390.00
360.00
Y-AXIS
*10¹
X-AXIS
*10¹

COMAIN 3

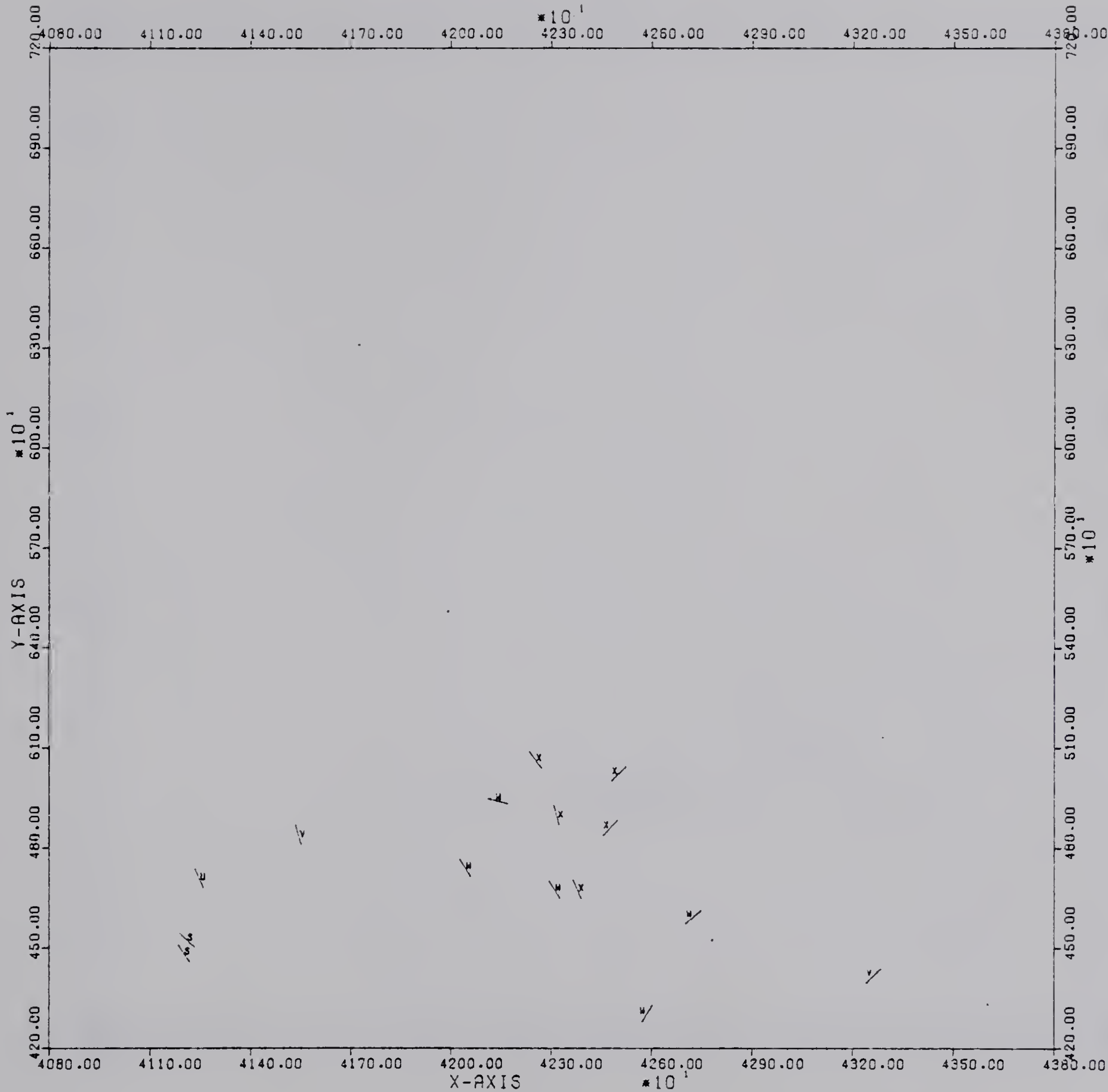

*10 1
3250.00
3300.00
3350.00
3400.00
3450.00
3500.00
3550.00
3600.00
3650.00
3700.00
3750.00
X-AXIS
Y-AXIS
270.00
320.00
370.00
420.00
470.00
520.00
570.00
620.00
670.00
720.00
770.00

DOMAIN 4



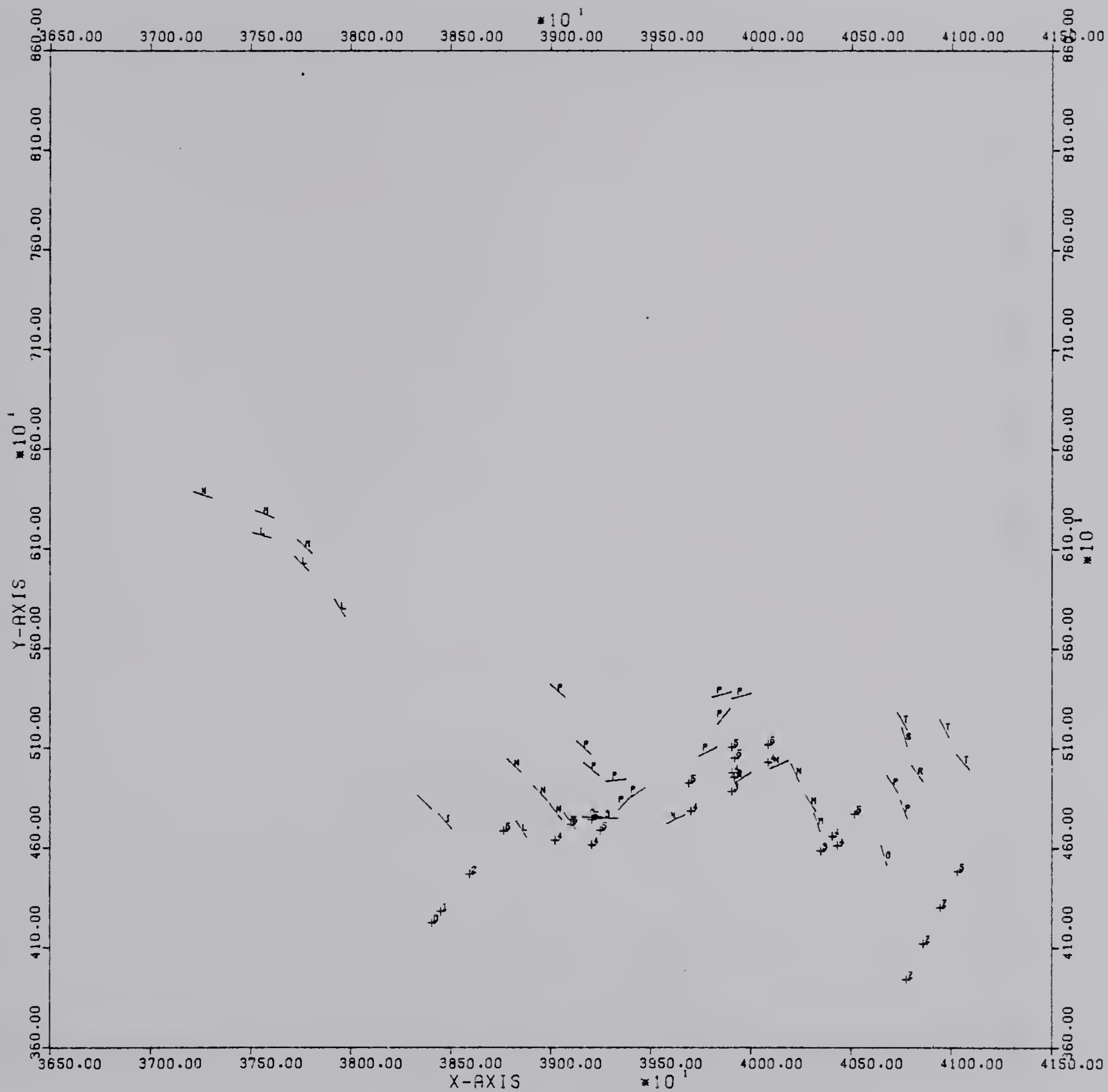
*10 1
3450.00
3480.00
3510.00
3540.00
3570.00
3600.00
3630.00
3660.00
3690.00
3720.00
3750.00
720.00
690.00
660.00
630.00
600.00
570.00
540.00
510.00
480.00
450.00
420.00
Y-AXIS
*10 1
X-AXIS
*10 1

DOMAIN 5

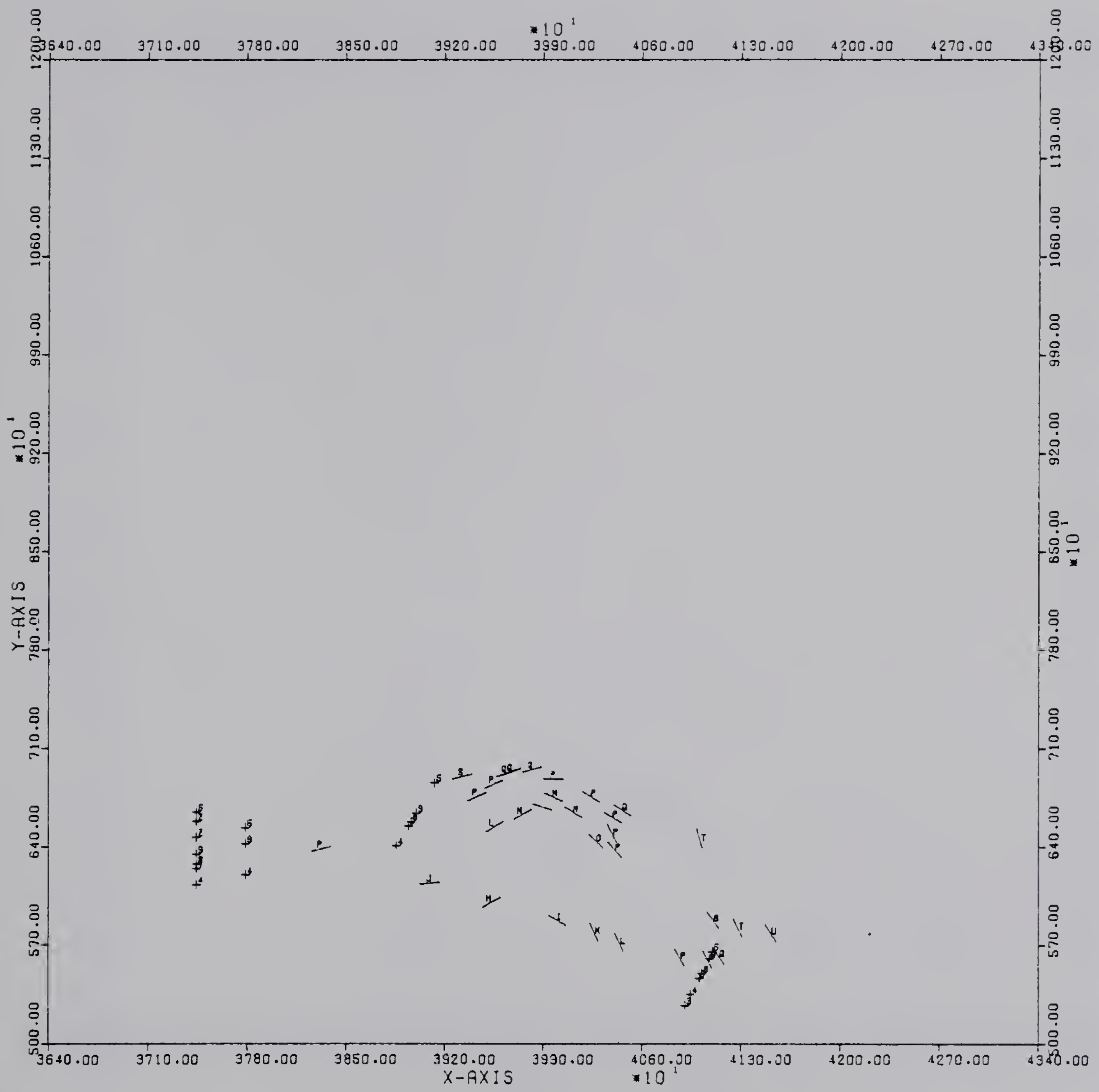


*10[1]
X-AXIS
*10[1]
Y-AXIS
*10[1]
4080.00
4110.00
4140.00
4170.00
4200.00
4230.00
4260.00
4290.00
4320.00
4350.00
4380.00
420.00
450.00
480.00
510.00
540.00
570.00
600.00
630.00
660.00
690.00
720.00

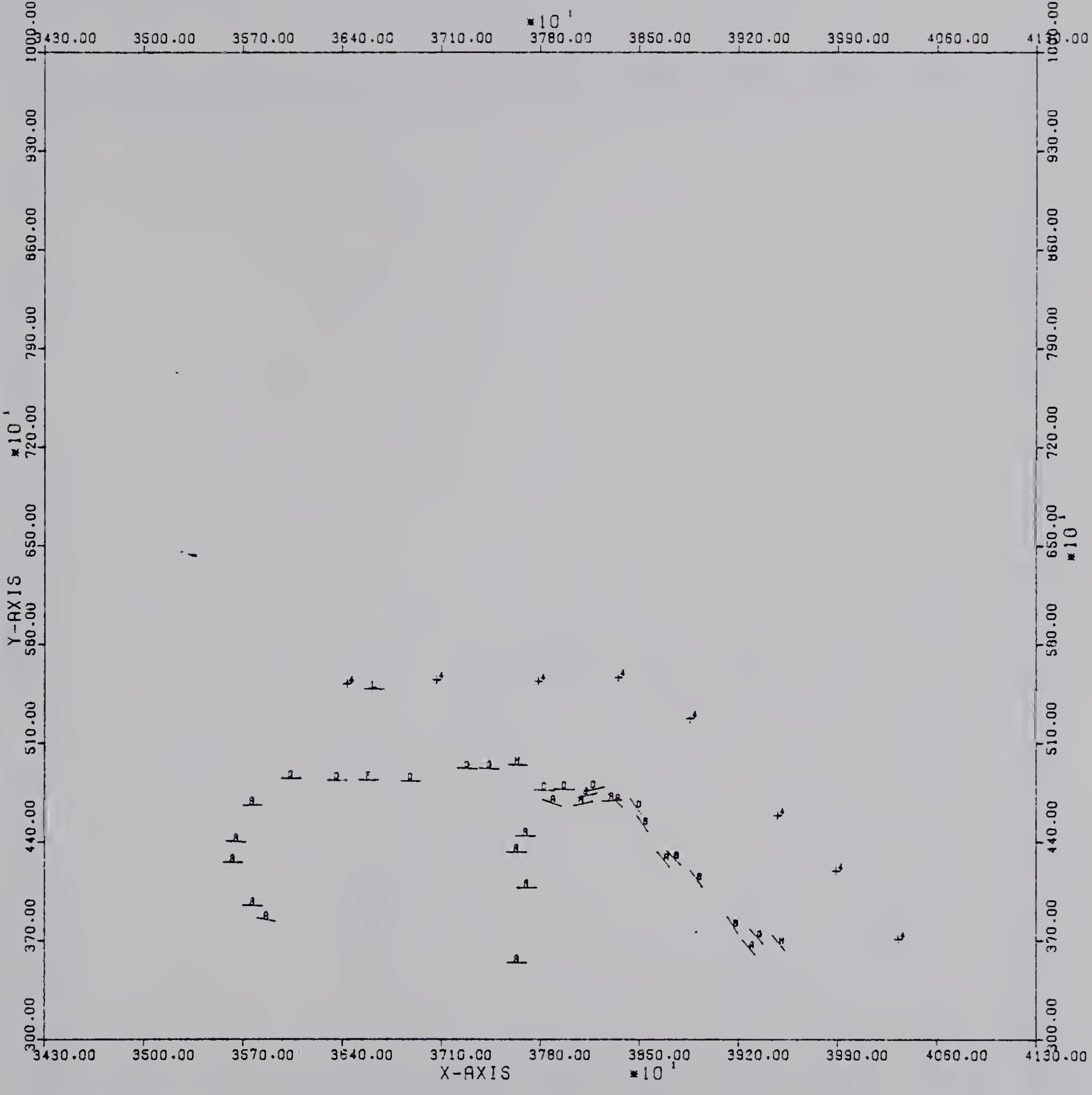
DOMAIN 6


*10 [1]
3650.00
3700.00
3750.00
3800.00
3850.00
3900.00
3950.00
4000.00
4050.00
4100.00
4150.00
860.00
810.00
760.00
710.00
660.00
610.00
560.00
510.00
460.00
410.00
360.00
Y-AXIS
*10 [1]
X-AXIS
*10 [1]

DOMAIN 7

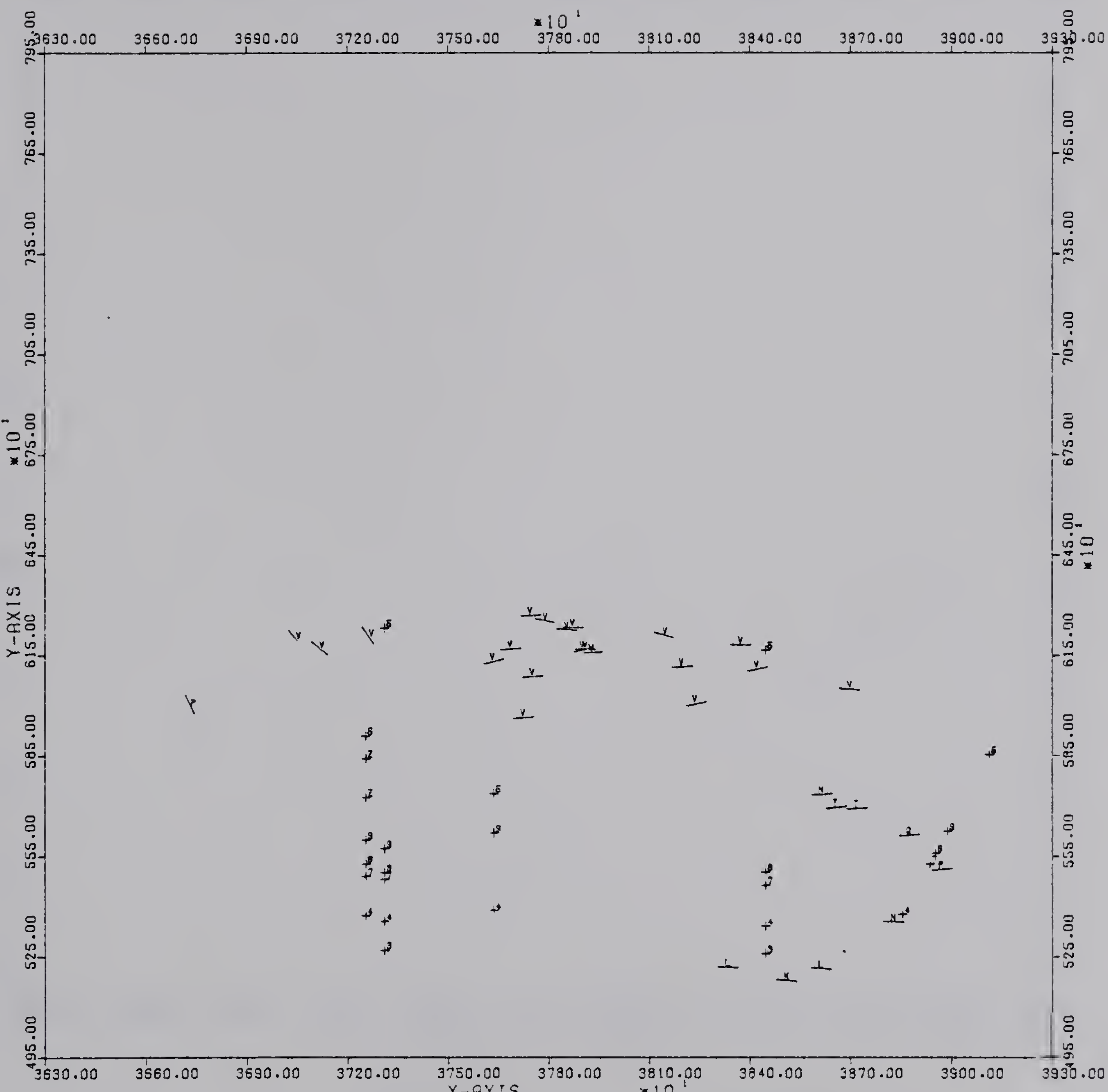

*10 1
3640.00
3710.00
3780.00
3850.00
3920.00
3990.00
4060.00
4130.00
4200.00
4270.00
4340.00
1200.00
1130.00
1060.00
990.00
920.00
850.00
780.00
710.00
640.00
570.00
500.00
Y-AXIS
X-AXIS

DOMAIN 8



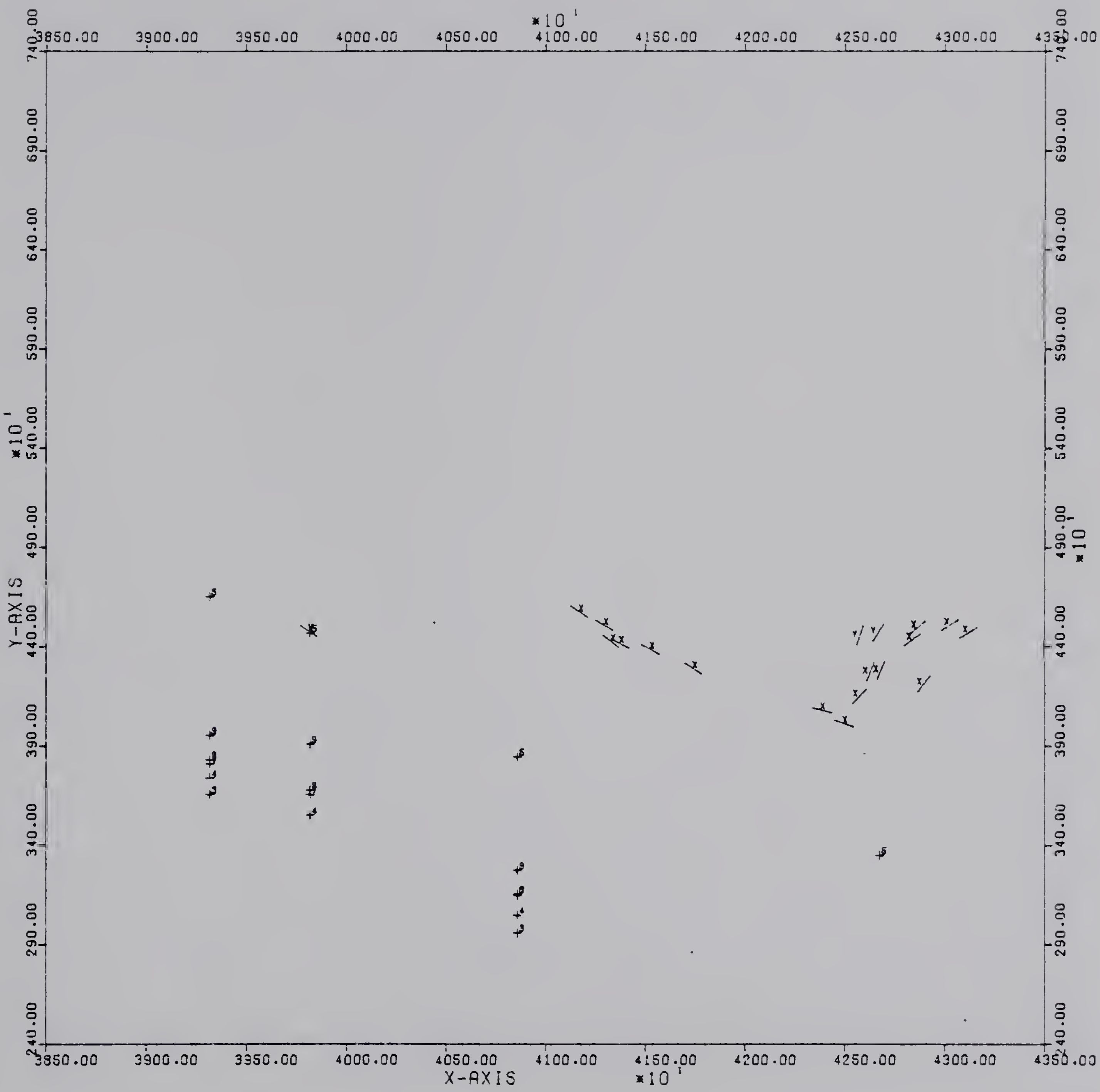
*10¹
3430.00 3500.00 3570.00 3640.00 3710.00 3780.00 3850.00 3920.00 3990.00 4060.00 4130.00
Y-AXIS *10¹
300.00 370.00 440.00 510.00 580.00 650.00 720.00 790.00 860.00 930.00 1000.00
X-AXIS *10¹

DOMAIN 9



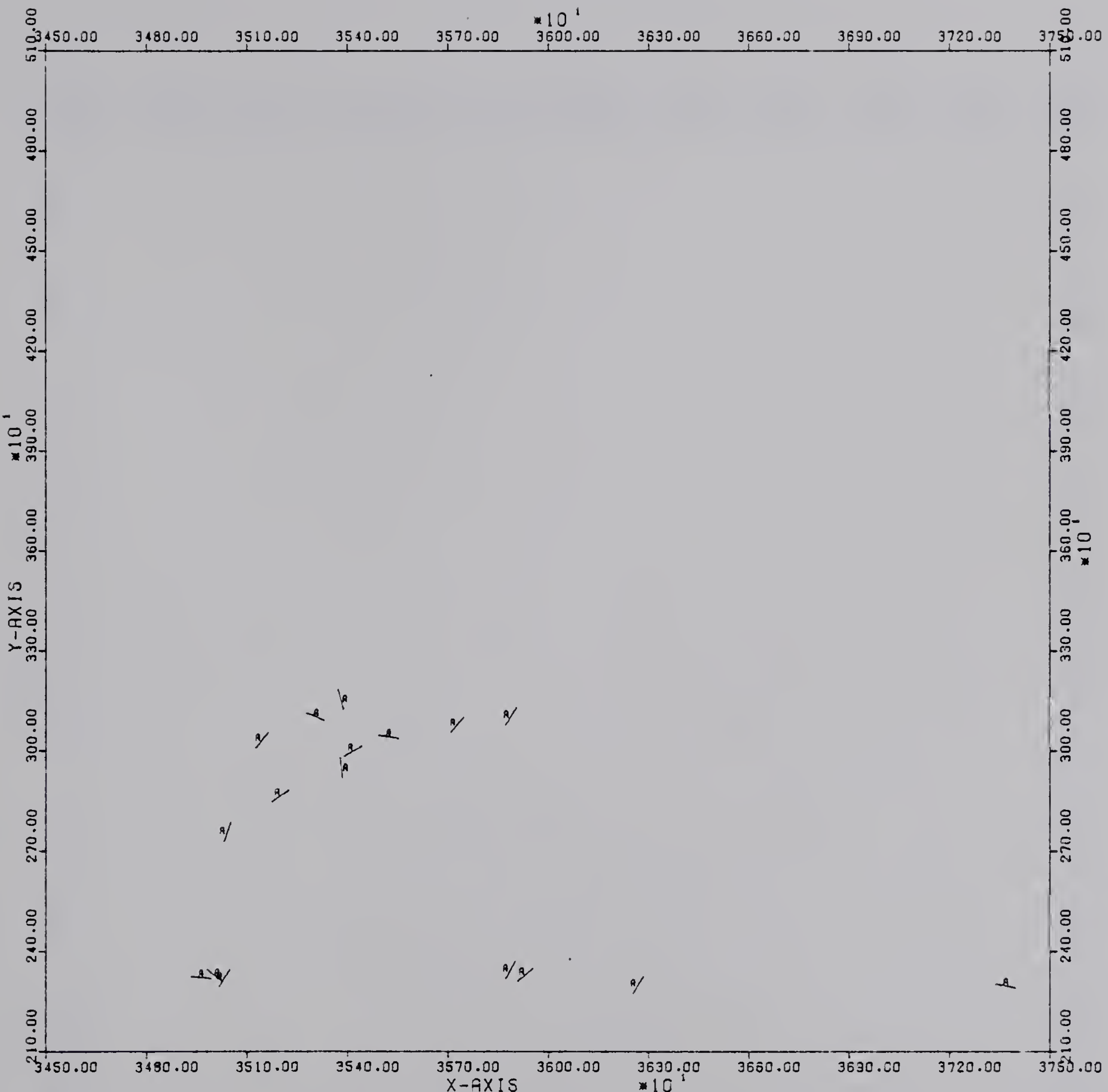
*10 [1]
3630.00
3660.00
3690.00
3720.00
3750.00
3780.00
3810.00
3840.00
3870.00
3900.00
3930.00
795.00
765.00
735.00
705.00
675.00
645.00
615.00
585.00
555.00
525.00
495.00
Y-AXIS
X-AXIS

DOMAIN 10

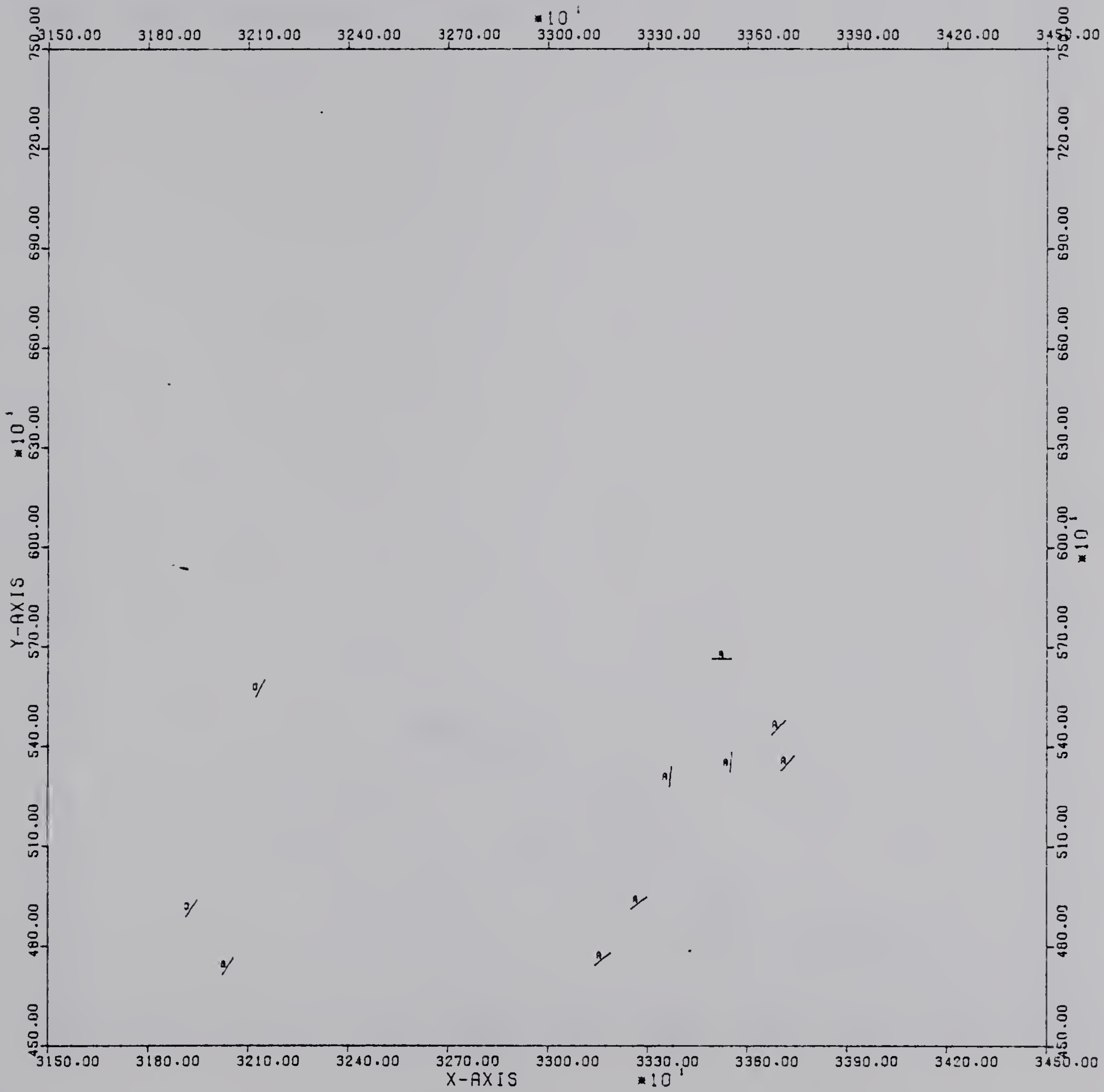


X-AXIS
Y-AXIS
*10 ¹
3850.00
3900.00
3950.00
4000.00
4050.00
4100.00
4150.00
4200.00
4250.00
4300.00
4350.00
240.00
290.00
340.00
390.00
440.00
490.00
540.00
590.00
640.00
690.00
740.00

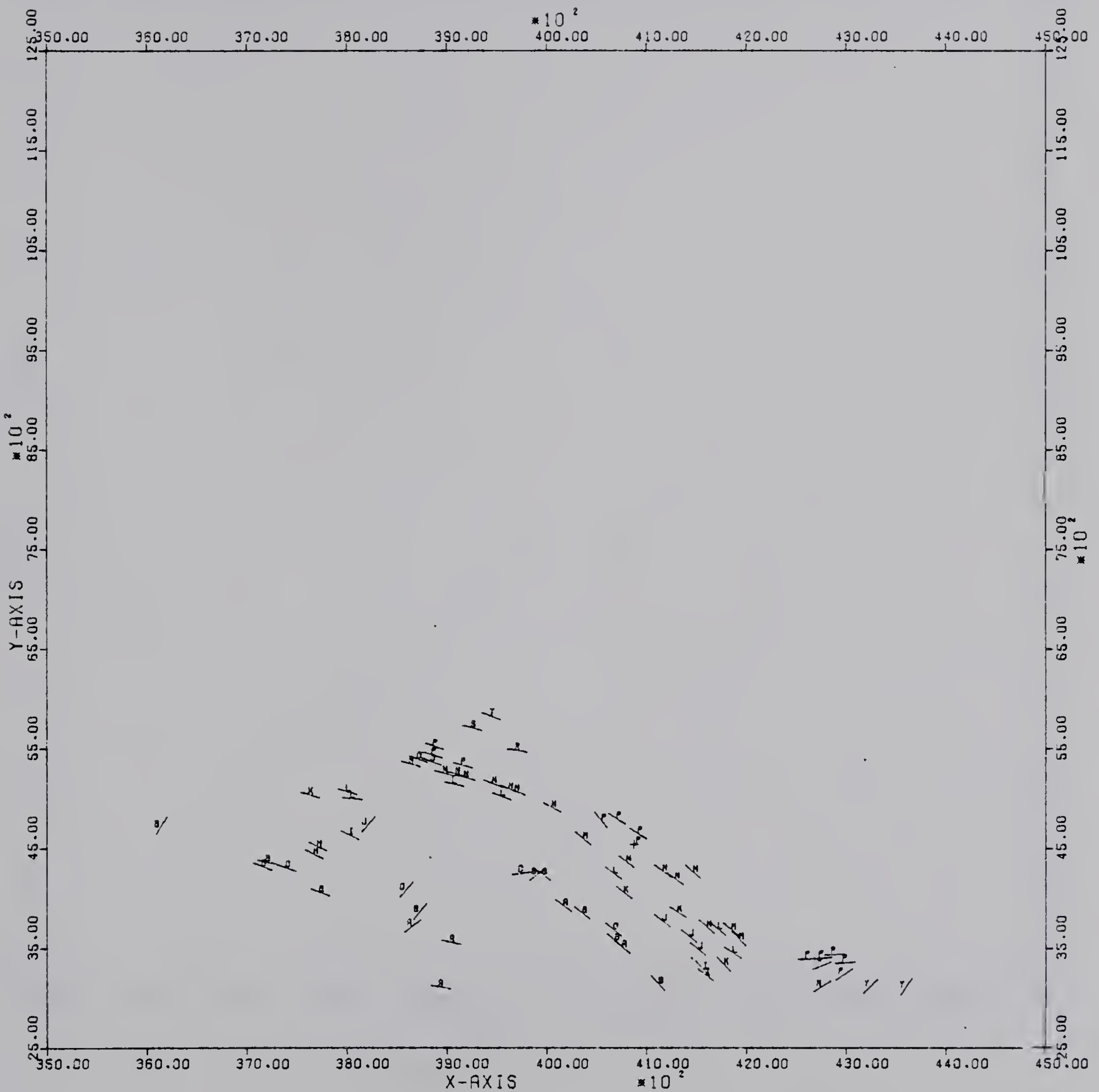
DOMAIN 11


*10^1
3450.00
3480.00
3510.00
3540.00
3570.00
3600.00
3630.00
3660.00
3690.00
3720.00
3750.00
510.00
480.00
450.00
420.00
390.00
360.00
330.00
300.00
270.00
240.00
210.00
Y-AXIS
X-AXIS

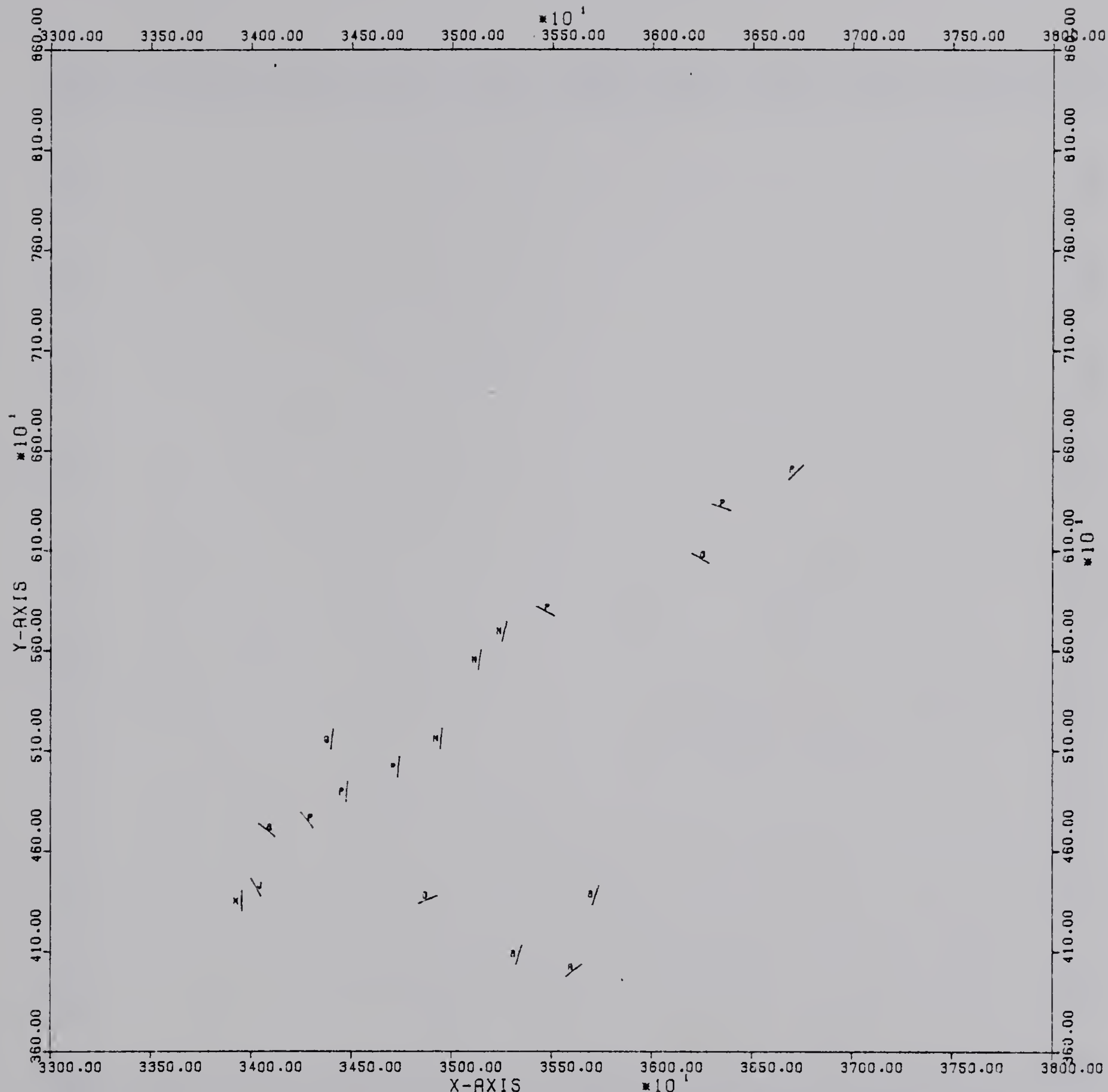
DOMAIN 12


*10 1
3150.00
3180.00
3210.00
3240.00
3270.00
3300.00
3330.00
3360.00
3390.00
3420.00
3450.00
750.00
720.00
690.00
660.00
630.00
600.00
570.00
540.00
510.00
480.00
450.00
Y-AXIS
X-AXIS

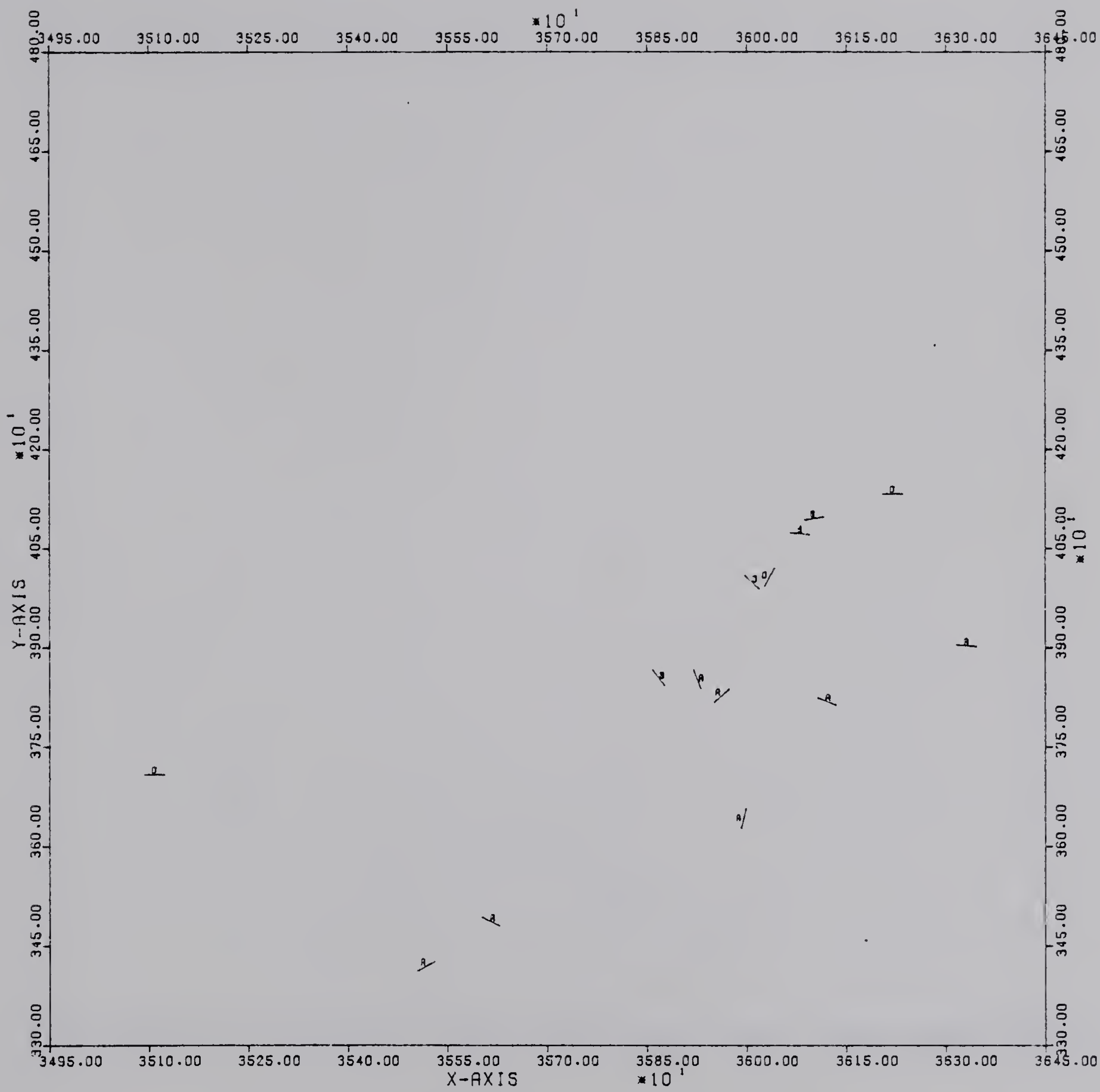
DOMAIN 13


*10²
350.00
360.00
370.00
380.00
390.00
400.00
410.00
420.00
430.00
440.00
450.00
125.00
115.00
105.00
95.00
85.00
75.00
65.00
55.00
45.00
35.00
25.00
Y-AXIS
X-AXIS

DOMAIN 14

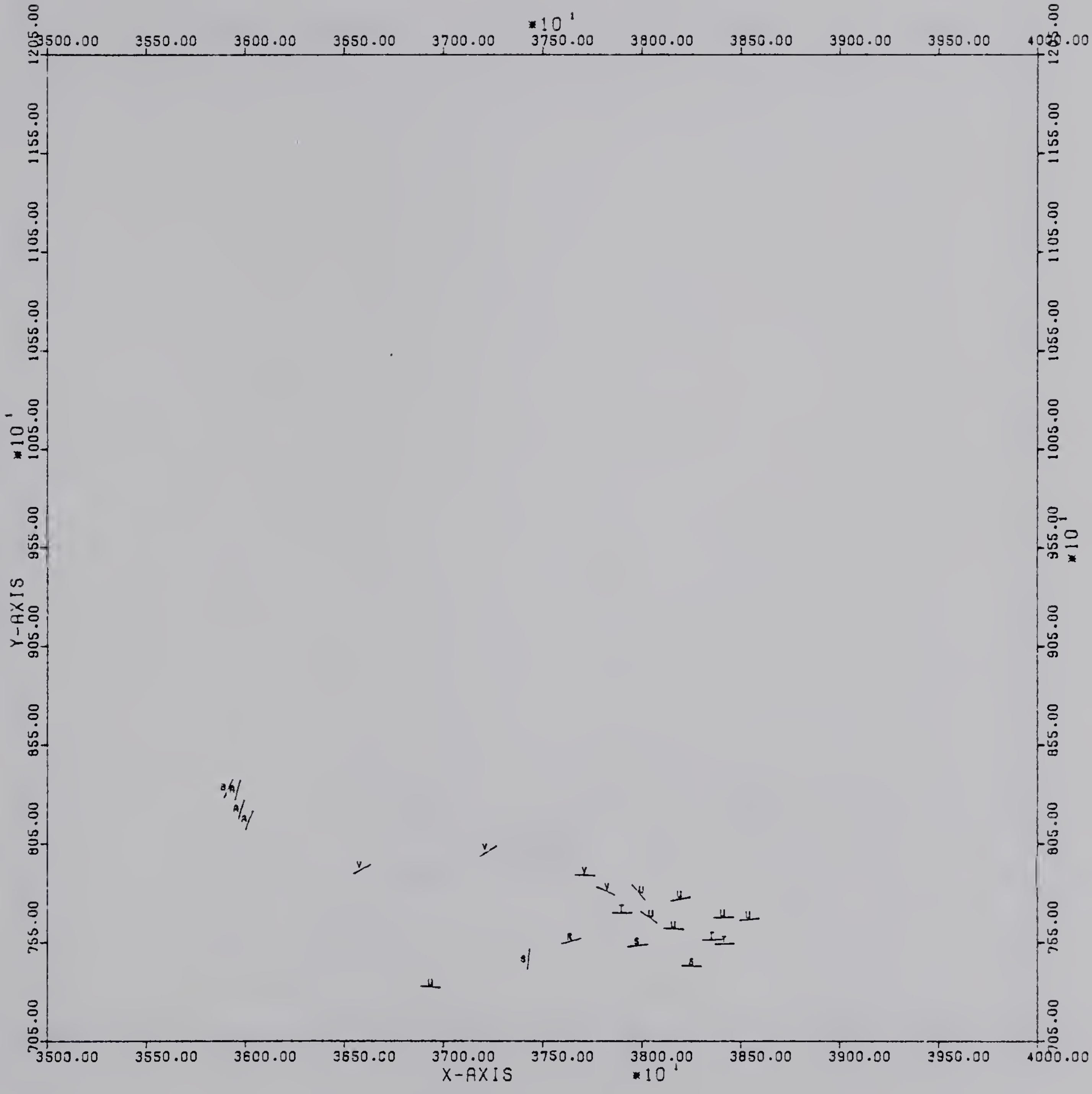

*10 1
3300.00
3350.00
3400.00
3450.00
3500.00
3550.00
3600.00
3650.00
3700.00
3750.00
3800.00
860.00
810.00
760.00
710.00
660.00
610.00
560.00
510.00
460.00
410.00
360.00
Y-AXIS
*10 1
X-AXIS
*10 1

DOMAIN 15

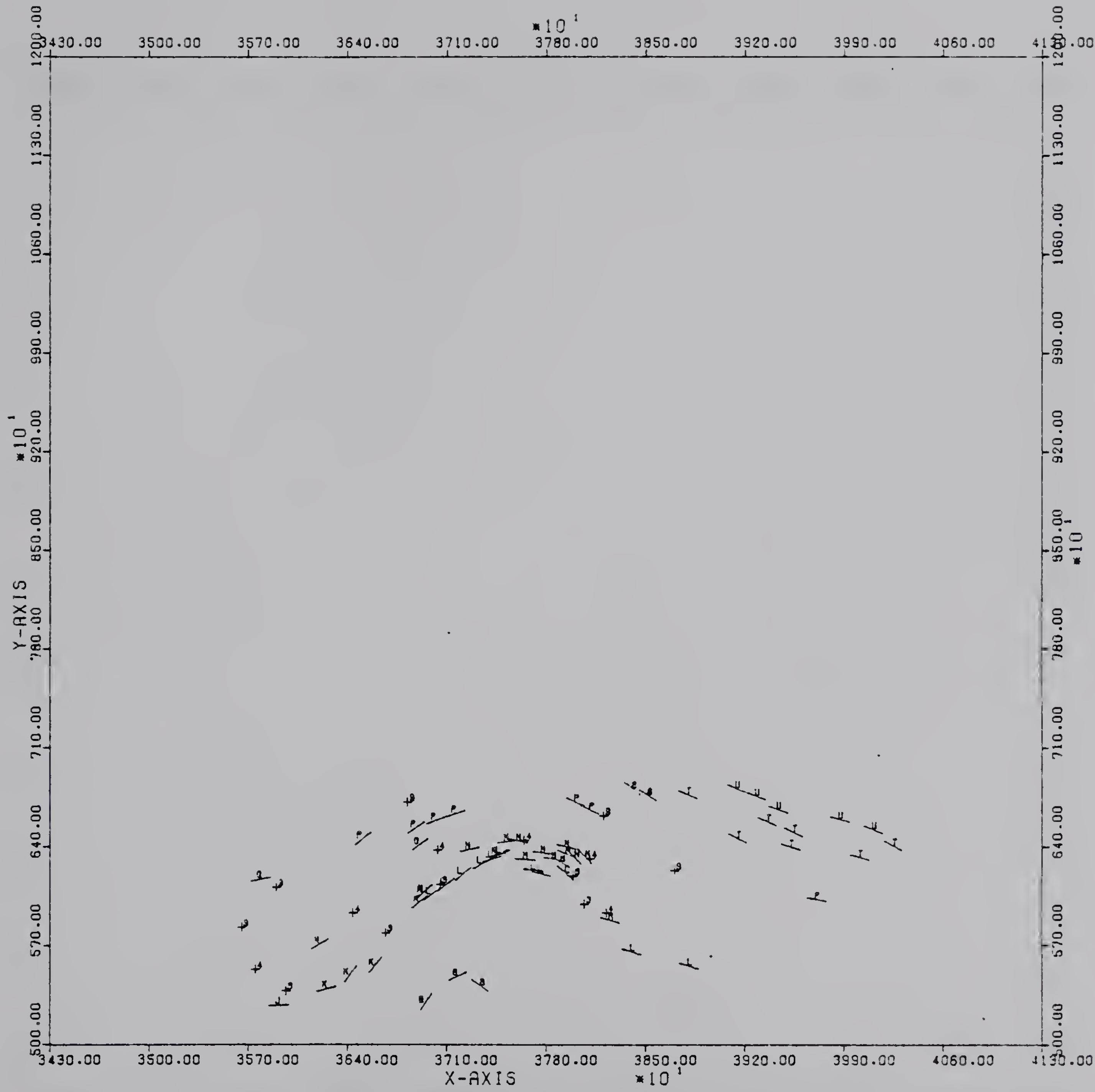


*10 [1]
3495.00
3510.00
3525.00
3540.00
3555.00
3570.00
3585.00
3600.00
3615.00
3630.00
3645.00
X-AXIS
Y-AXIS
330.00
345.00
360.00
375.00
390.00
405.00
420.00
435.00
450.00
465.00
480.00

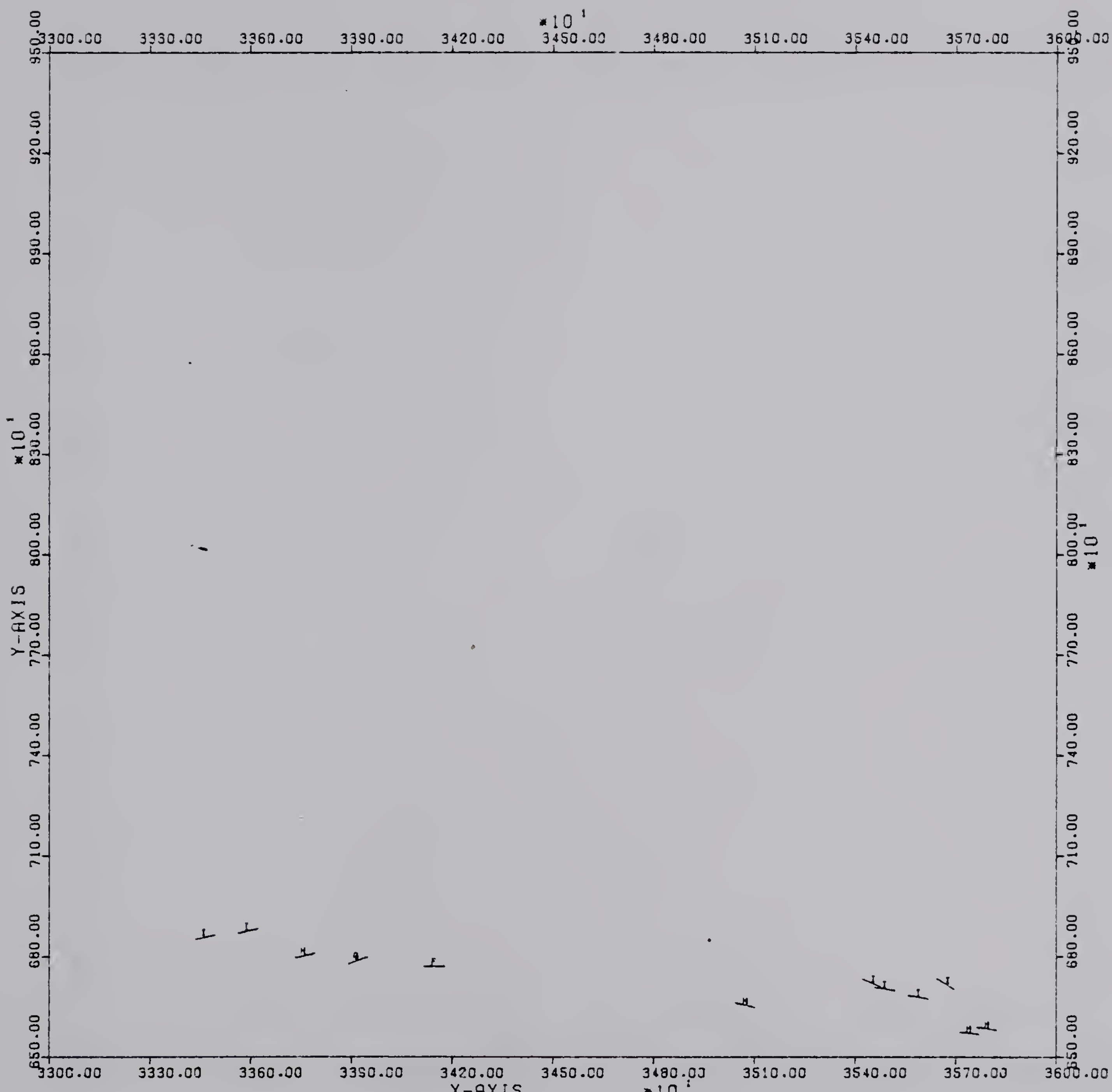
DOMAIN 16


*10¹
3500.00
3550.00
3600.00
3650.00
3700.00
3750.00
3800.00
3850.00
3900.00
3950.00
4000.00
X-AXIS
*10¹
Y-AXIS
*10¹
705.00
755.00
805.00
855.00
905.00
955.00
1005.00
1055.00
1105.00
1155.00
1205.00

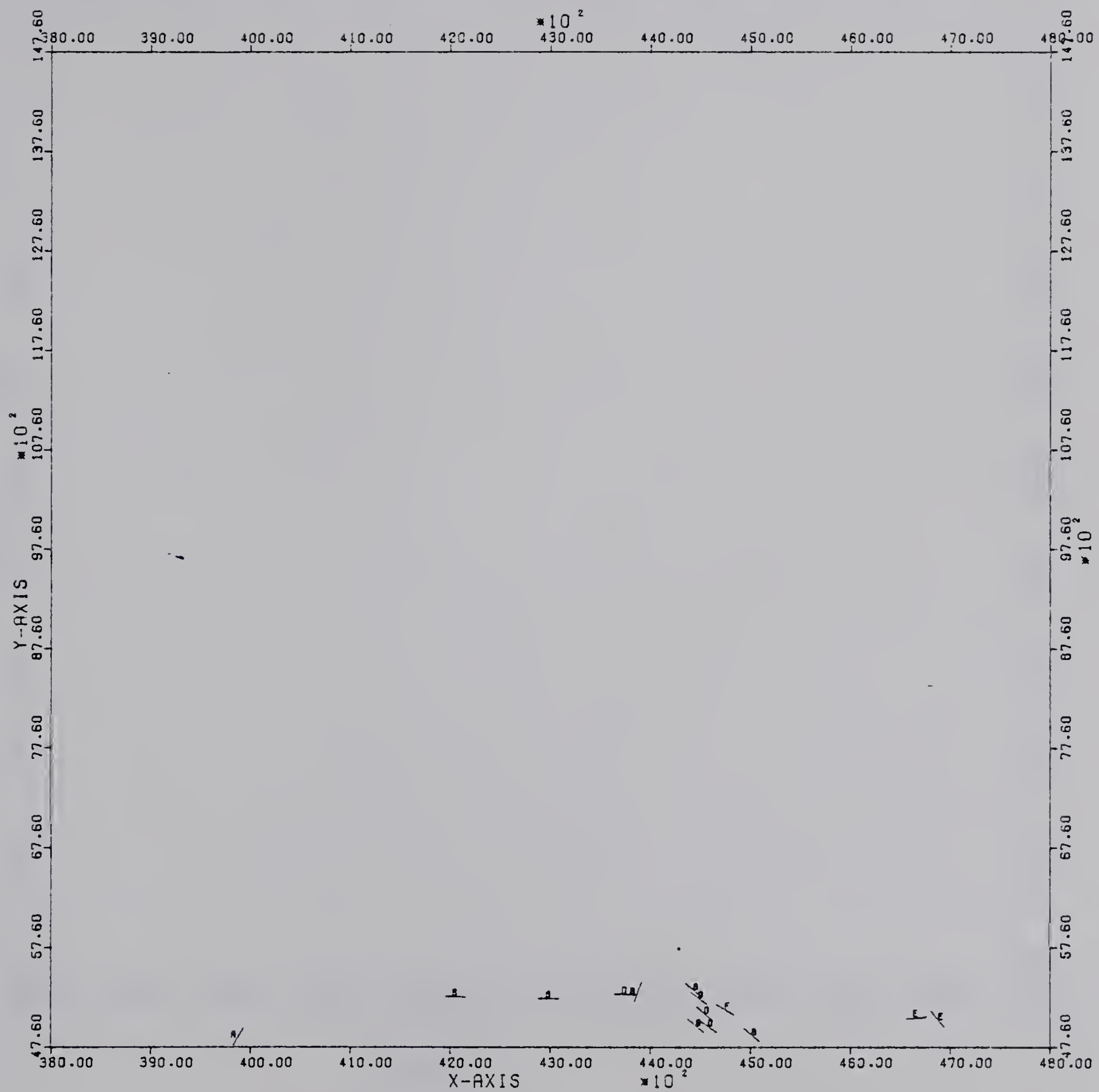
DOMAIN 17


*10 1
3430.00
3500.00
3570.00
3640.00
3710.00
3780.00
3850.00
3920.00
3990.00
4060.00
4130.00
1200.00
1130.00
1060.00
990.00
920.00
850.00
780.00
710.00
640.00
570.00
500.00
Y-AXIS
X-AXIS

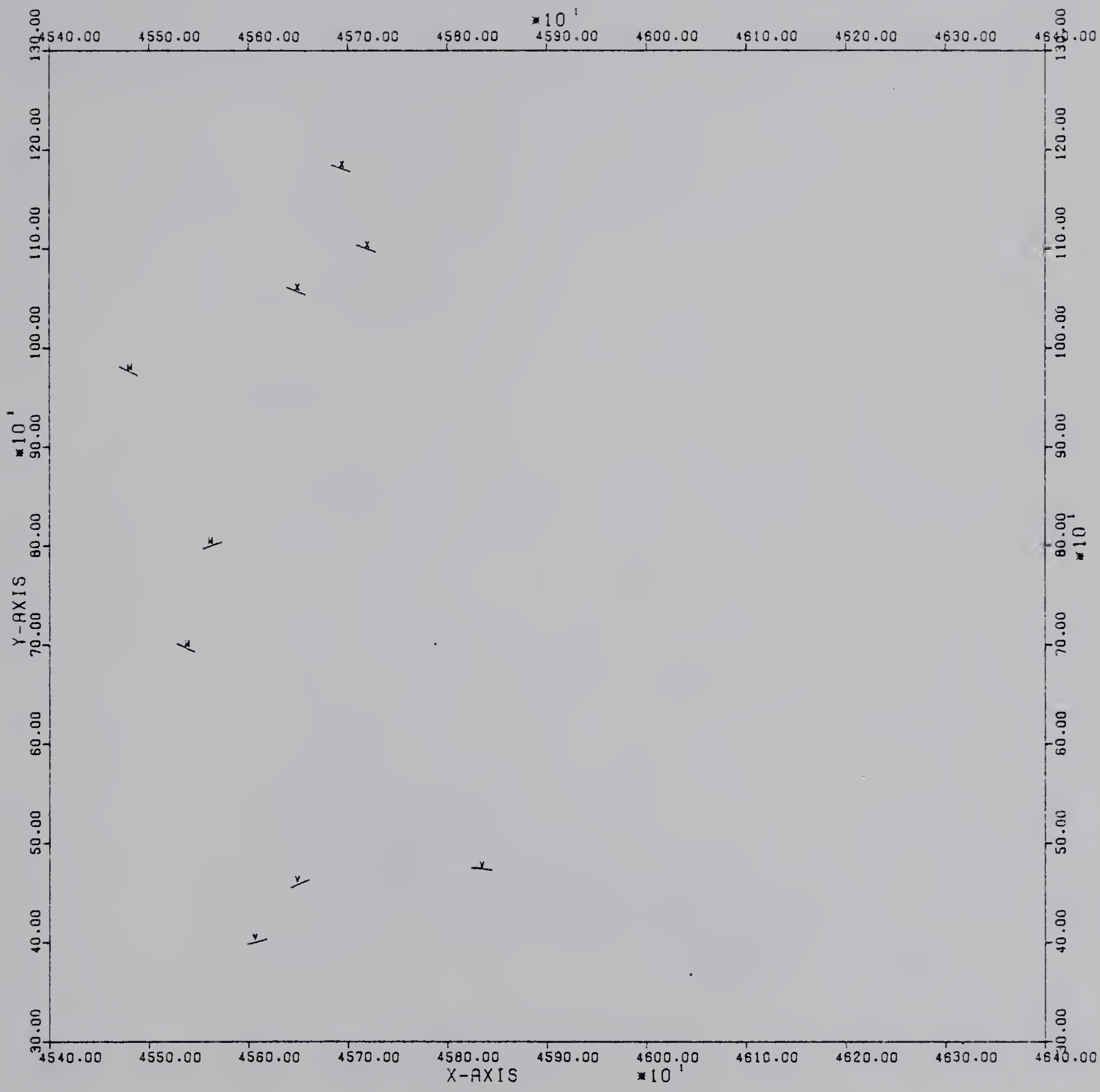
DOMAIN 18



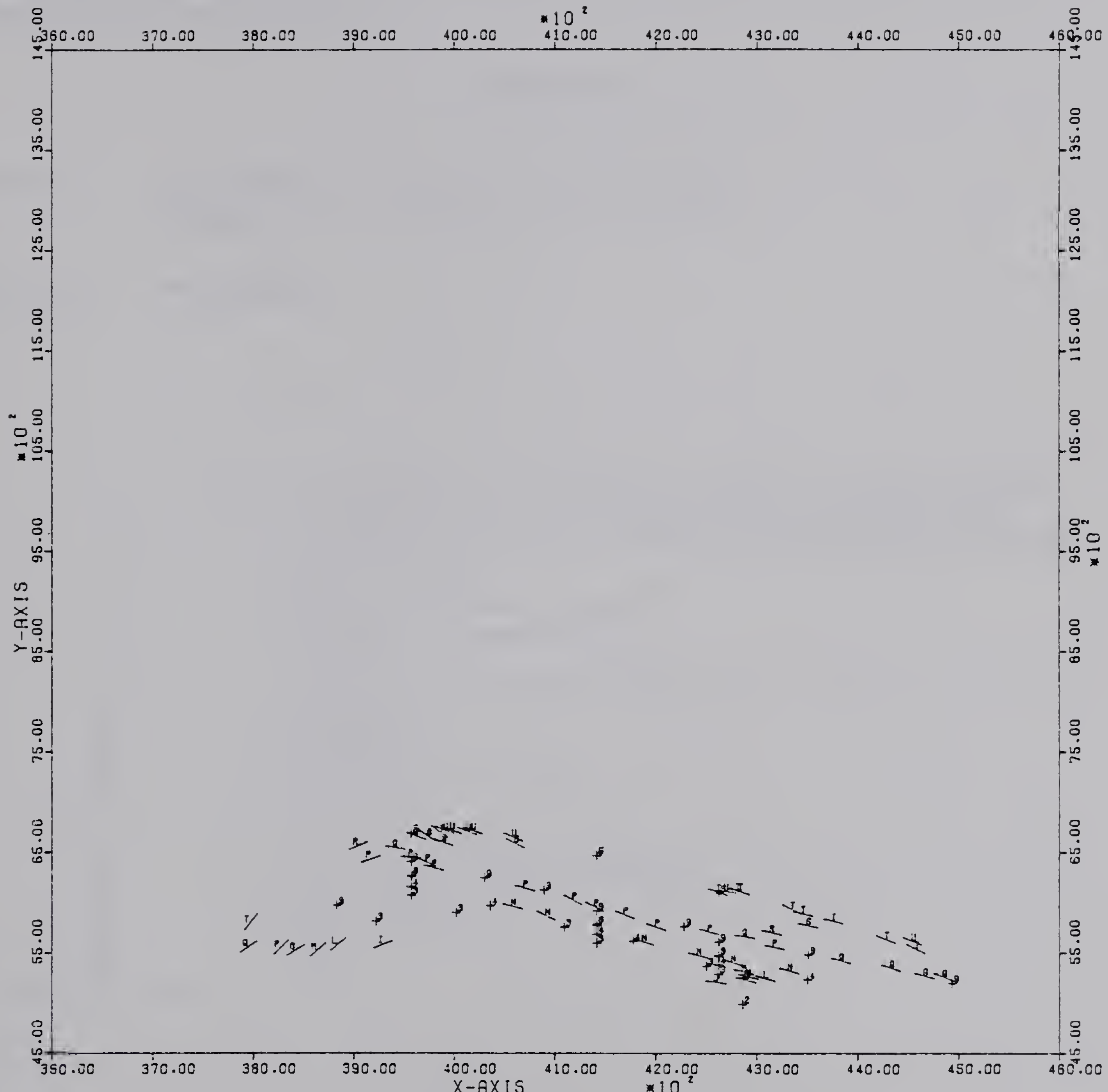
DOMAIN 19



DOMAIN 20


*10 1
4540.00
4550.00
4560.00
4570.00
4580.00
4590.00
4600.00
4610.00
4620.00
4630.00
4640.00
30.00
40.00
50.00
60.00
70.00
80.00
90.00
100.00
110.00
120.00
130.00
X-AXIS
Y-AXIS
*10 1

DOMAIN 21



*10²
360.00
370.00
380.00
390.00
400.00
410.00
420.00
430.00
440.00
450.00
460.00
145.00
135.00
125.00
115.00
105.00
95.00
85.00
75.00
65.00
55.00
45.00
Y-AXIS
X-AXIS

DOMAIN 22

APPENDIX 7.

Listings of the programs, with appropriate inputs and outputs, used to generate the coordinates of points for structure contouring.

DATAFORM

inputs 4=-PROFILE (output from SECT5)
5=DOMX

outputs 6=PROFILE

```
      C ---  DATAFORM IS DESIGNED TO REFORMAT PROFILE OUTPUT
      C ---  FROM SECT5 WITH DATA FROM DOMAIN FILES INTO A
      C ---  FORMAT SUITABLE FOR STRUCTURE CONTOURING PROGRAMS
             INTEGER D
             DO 1 I=1,100
           9 READ(4,10,END=2)X,Y,PIT
           7 READ(5,11,END=5)D,N,M
             SD=D*1.
           4 WRITE(6,12)X,Y,PIT,SD,N,M
             GO TO 6
           5 CONTINUE
             WRITE(6,13)X,Y,PIT
           6 CONTINUE
           1 CONTINUE
          10 FORMAT(6X,3F12.1)
          11 FORMAT(62X,I4,4X,I4,2X,I2)
          12 FORMAT(4F8.1,2I5)
          13 FORMAT(3F8.1)
           2 STOP
             END
END OF FILE
```

HORIZON

inputs 4=*SOURCE*

- ddap = dip direction of the axial plane
- diap = dip of the axial plane
- tnp = trend of the normal to the profile
- pnp = plunge of the normal to the profile
- cs = stratigraphic position (in feet) of the coal seam above the formation base
- xprof, yprof = coordinates of the lower left-hand corner of the profile
- scale = scale in feet per inch

5=PROFILE

outputs 6=COALPROF (file containing the profile coordinates, slope and weight of points calculated to be on the coal seam)

9=profile plot of the points on the coal seam

```
C ---  HORIZON IS DESIGNED TO CALCULATE COORDINATES AND
C ---  SLOPES ON COAL SEAM TO BE CONTOURED FROM PROFILE
C ---  OUTCROP POSITIONS
      INTEGER CS
      DTR=1.745329E-2
C
      READ(4,10)DDAP,DIAP,TNP,PNP,CS,XPROF,YPROF,SCALE
      CALL PLOTS
C ---  DRAW BOUNDARIES
      XPR=XPROF/10.
      YPR=YPROF/10.
      SCA=SCALE/10.
      CALL AXZER(1.0,1,-1)
      CALL AXIS2(1.0,1.0,'X-AXIS  *10',-11,10.0,0.0,XPR,SCA,1.0)
      CALL AXIS2(11.0,1.0,' ',-1,10.0,90.0,YPR,SCA,-1.0)
      CALL AXIS2(1.0,1.0,'Y-AXIS  *10',11,10.0,90.0,YPR,SCA,-1.0)
      CALL AXIS2(1.0,11.0,' ',1,10.0,0.0,XPR,SCA,1.0)
      TAP=DDAP+180.
      PAP=90.-DIAP
      TAP=TAP-450.
      TNP=TNP-450.
      DNP=(TNP+180.)*DTR
      DIP=(90.-PNP)*DTR
C ---  DETERMINE DIRECTION COSINES OF THE NORMAL
C ---  TO THE AXIAL PLANE AND THE FOLD-AXIS
      A=COS(DTR*TAP)*COS(DTR*PAP)
      B=SIN(DTR*TAP)*COS(DTR*PAP)
      C=SIN(DTR*PAP)
      D=COS(DTR*TNP)*COS(DTR*PNP)
      E=SIN(DTR*TNP)*COS(DTR*PNP)
      F=SIN(DTR*PNP)
C ---  FIND THE DIRECTION COSINES OF THE LINE OF INTERSECTION
C ---  OF THE AXIAL PLANE AND PROFILE (PROJECTION LINE)
  200 BL=(B*F-C*E)/(A*E-B*D)
      BM=(-F-D*BL)/E
      XN=SQRT(1/(1+BL**2+BM**2))
      XL=XN*BL
      XM=XN*BM
```

```
C ---  FIND THE TREND AND PLUNGE AND THE PITCH OF THE
C ---  LINE OF PROJECTION ON THE PROFILE
  201 PIL=ASIN(XA)
      TIL=DNP-(90*DTR)+ATAN(COS(DIP)*TAN(ASIN(SIN(PIL)/SIN(DIP)
      DIP=TIL-(DNP-90*DTR)
      APP=-(ASIN(COS(DIP)*COS(90*DTR-PIL)))
      AI=-4.61/500.
C ---  READ IN PROFILE DATA
  202 DO 1 I=1,100
      READ(5,11,END=2)X,Y,PIT,SD
      POT=PIT
      SLOPE=-TAN(PIT*DTR)
      IF(PIT .EQ. -999.9) GO TO 100
      IF(PIT .GT. 90.)PIT=PIT-180.
  210 IF(SD .EQ. -999.9)GO TO 4
C ---  DETERMINE STRATIGRAPHIC SEPARATION BETWEEN OUTCROP
C ---  AND COAL SEAM
      CD=CS-SD
      CB=ABS(CD)
C ---  CALCULATE WEIGHT
      WT=2.7182818**(AI*CB)
      POL=(PIT-90.)*DTR

C ---  FIND ANGLE BETWEEN TRACES OF AXIAL PLANE AND BEDDING
      ANG=APP-POL
      IF(ANG .GT. 75*DTR) GO TO 5
      IF(ANG .LT. -75*DTR) GO TO 5
      CL=CD/COS(ANG)
C ---  FIND PROJECTED COORDS AND SLOPE OF COAL SEAM
  203 X1=(X+COS(APP)*CL)
      Y1=(Y-SIN(APP)*CL)
      GO TO 6
    5 X1=X+COS(PIT1*DTR)*CD
      Y1=Y+SIN(PIT1*DTR)*CL
C
    6 WRITE(6,12)X1,Y1,SLOPE,WT
      GO TO 3
  100 IF(ABS(CD) .GT. 20.)GO TO 4
      SLOPE=0.0
      WT=1.0
      WRITE(6,12)X,Y,SLOPE,WT
      X1=X
      Y1=Y
    3 CONTINUE
      XO=((X1+SCALE)-XPROF)/SCALE
      YO=((Y1+SCALE)-YPROF)/SCALE
      CALL SYMBOL(XO,YO,0.05,004,0.0,-1)
    4 CONTINUE
    1 CONTINUE
   10 FORMAT(4F8.1,I4,3F8.1)
   11 FORMAT(4F8.1)
   12 FORMAT(F8.1,F8.1,F8.4,F10.6)
    2 CALL PLOT(0.,0.,999)
      STOP
      END
END OF FILE
```

SLOPE

inputs 1=COALPROF
2=*SOURCE*
a = trend of fold-axis
b = plunge of fold-axis
xprof, yprof = coordinates of the lower left-hand corner of the profile
scale = scale of the profile in feet per inch
ri = distance to 1% influence for the weighting function
xmin = lowest profile X-coordinate to be calculated
xmax = highest profile X-coordinate to be calculated
3=DOMX (with additional map coordinates added from within the domain)

outputs 5=*PRINT* (listing of map coordinates and slopes of the coal seam)
6=COALMAP (map coordinates and slopes of the coal seam for contouring)
9=COALPLOT (profile plot of the coal seam locations projected parallel to the fold-axis)

```
C ---   TO GENERATE COORDINATES FOR STRUCTURE CONTOURING
      DIMENSION TM1(9),TM2(9),XX(200),YY(200),DP(200),WT(200)
      REAL LP,MP,NP,LM,MM,NM,PLUN
      INTEGER X,Y,ZI
      REAL OB
      READ(2,20) A,B,XPROF,YPROF,SCALE,RI,XMIN,XMAX
      WRITE(5,24) A,B
      AI=-4.61/RI
      CALL PLOTS
      XPR=XPROF/10.
      YPR=YPROF/10.
      SCA=SCALE/10.
      CALL AX2EP(1.0,1,-1)
      CALL AXIS2(1.0,1.0,'X-AXIS  *10',-11,10.0,0.0,XPR,SCA,1.0)
      CALL AXIS2(11.0,1.0,' ',-1,10.0,90.0,YPR,SCA,-1.0)
      CALL AXIS2(1.0,1.0,'Y-AXIS  *10',11,10.0,90.0,YPR,SCA,-1.0)
      CALL AXIS2(1.0,11.0,' ',1,10.0,0.0,XPR,SCA,1.0)
      DTR=1.745329E-2
      A=A*DTR
      B=B*DTR
      N=1
      DO 1 J=1,200
      READ(1,21,END=2) XX(J),YY(J),DP(J),WT(J)
      N=N+1
    1 CONTINUE
    2 SA=SIN(A)
      CA=COS(A)
      SB=SIN(B)
      CB=COS(B)
C ---  CREATE TRANSFORMATION MATRIX TM1
      TM1(1)=CA
      TM1(2)=-SA
      TM1(3)=0.0
      TM1(4)=SA*SB
      TM1(5)=CA*SB
      TM1(6)=CB
      TM1(7)=-SA*CB
```

```
      TM1(8)=-CA*CB
      TM1(9)=SB
C --- CREATE TRANSFORMATION MATRIX TM2
      TM2(1)=-SA
      TM2(2)=CA*SB
      TM2(3)=CA*CB
      TM2(4)=CA
      TM2(5)=SA*SB
      TM2(6)=SA*CB
      TM2(7)=0.0
      TM2(8)=-CB
      TM2(9)=SB
      WRITE(5,25)
      WRITE(5,26)
 1000 READ(3,22,END=4)X,Y,ZI
      TOP=ZI*1.0
C --- TRANSFORM MAP COORDINATES TO PROFILE COORDINATES
      XP=X*TM1(1)+Y*TM1(2)
      YP1=X*TM1(4)+Y*TM1(5)
      ZP=-(X*TM1(7)+Y*TM1(8))
C --- CALCULATE THE PROFILE COORDINATES OF THE HORIZON OF INTEREST
      IF(XP .LT. XMIN)GO TO 9
      IF(XP .GT. XMAX)GO TO 9
      SY=0.0
      SDP=0.0
      SW=0.0
      SWD=0.0
      DO 100 I=1,N
      DX=XP-XX(I)
      Y1=YY(I)+DX*DP(I)
      DR=ABS(DX)
C --- DETERMINE WEIGHT
      W=(2.7182818**(A1*DR))*WT(I)
   98 SW=SW+W
      SY=SY+Y1*W
      SDP=SDP+DP(I)*W
      IF(DP(I) .EQ. 0.0) GO TO 101
      SWD=SWD+W
  101 CONTINUE
  100 CONTINUE
      YP=SY/SW
      IF(SWD .EQ. 0.0) GO TO 179
C --- DETERMINE SLOPE
      SLOPE=SDP/SWD
      GO TO 180
  179 SLOPE=0.0
C --- CORRECT COORDINATES TO SLOPE OF PROFILE
  180 YSEP=YP-YP1
      ZCBA=YSEP*TAN(B)
      ZP=ZP-ZCBA
      XO=((XP+SCALE)-XPROF)/SCALE
      YO=((YP+SCALE)-YPROF)/SCALE
      CALL SYMBOL(XO,YO,0.05,004,0.0,-1)
C --- TRANSFORM PROFILE COORDINATES TO MAP COORDINATES
      XJ=XP*TM2(1)+YP*TM2(2)+ZP*TM2(3)
      YJ=XP*TM2(4)+YP*TM2(5)+ZP*TM2(6)
      ZJ=-(XP*TM2(7)+YP*TM2(8)+ZP*TM2(9))
C --- DETERMINE THE APPARENT DIP OF THE HORIZON ALONG THE X AND Y
C --- MAP AXES
C --- ANGLE BETWEEN PROFILE X Y AND Z AND THE POLE TO THE HORIZON
```

```
      IF(SLOPE .LT. 0.0)GO TO 50
      IF(SLOPE .EQ. 0.0) GO TO 500
      XA=ATAN(1./SLOPE)
      YA=-(ATAN(SLOPE))
      GO TO 51
   50 XA=ATAN(1./SLOPE)
      YA=ATAN(SLOPE)
   51 CONTINUE
C ---  DIRECTION COSINES OF THE POLE
      LP=COS(90*DTR+YA)
      MP=COS(90*DTR+XA)
      NP=COS(90*DTR)
C ---  TRANSFORM THE DIRECTION COSINES TO THE MAP COORDINATE SYSTEM
      LM=LP*TM2(1)+MP*TM2(2)
      MM=LP*TM2(4)+MP*TM2(5)
      NM=-(LP*TM2(7)+MP*TM2(8))
C ---  CONVERT THE DIRECTION COSINES TO A TREND AND PLUNGE
      IF(NM .LT. -1.0) NM=-1.0
      IF(NM .GT. 1.0) NM=1.0
      PLUN=ASIN(NM)
      TRN=(LM/COS(PLUN))
      IF(TRN .LT. -1.0) TRN=-1.0
      IF(TRN .GT. 1.0) TRN=1.0
      TREN=ASIN(TRN)
C ---  CONVERT THE TREND AND PLUNGE TO A DIP DIRECTION AND DIP
  201 DIPDIR=(180*DTR)+TREN
      DIP=(90*DTR)-PLUN
C ---  FIND THE APPARENT DIP OF THE HORIZON ON THE N-S (X) AXIS AND
C ---  ON THE E-W (Y) AXIS
      ADX=SIN(DIPDIR)*TAN(DIP)
      ADY=SIN(90*DTR-DIPDIR)*TAN(DIP)
      GO TO 501
C ---  CALCULATE OVERBURDEN THICKNESS
  500 ADX=0.0
      ADY=0.0
  501 OB=TOP-ZJ
C ---  WRITE NEW COORDINATES
      WRITE(5,23)YJ,XJ,ZJ,ADX,ADY,TOP,OB
      WRITE(6,23)YJ,XJ,ZJ,ADX,ADY,TOP,OB
    9 CONTINUE
    3 CONTINUE
      GO TO 1000
   20 FORMAT(8F8.1)
   21 FORMAT(2F6.1,F6.4,F10.6)
   22 FORMAT(1X,3I5)
   23 FORMAT(7F11.3)
   24 FORMAT('1',5X,10HFOLD AXIS ,2F8.1//)
   25 FORMAT(5X,21HPOINTS FOR CONTOURING/)
   26 FORMAT(7X,'X',10X,'Y',10X,'Z',7X,'X-SLOPE',
     *4X,'Y-SLOPE',6X,'TOPO',7X,'OB')
   27 FORMAT('ENTER THE INTERVAL OF 1% INFLUENCE')
   28 FORMAT(F8.1)
    6 CALL PLOT(0.,0.,999)
      STOP
      END
```

APPENDIX 8.

The following composite stratigraphic section of the Luscar Formation was compiled from partial sections measured on Packrat Creek, between grid points 28700E 23600N and 27230E 24480N, Campbell Flats, from 27230E 24480N to 26800E 26770N, Hells Creek, from 25350E 25950N to 23200E 25900N, and on Grande Mountain from 37750E 11050N to 37850E 10200N.

Feet	M	
		Unit D
1898.5	578.6	Interbedded sandstone, shale and siltstone; abrupt contact with overlying Shaftesbury Formation
1472.5	448.8	Granular and pebbly sandstone
1452.5	442.7	Medium-grained sandstone
1412.5	430.5	Granular and pebbly sandstone
1387.5	422.9	Interbedded sandstone, mudstone and siltstone with a 4 ft (1.2 m) pebble conglomerate at top
		Unit C
1270.5	387.2	Ridge-forming, lithic, medium- to fine- grained sandstone; flaggy in places with some siltstone and mudstone bands
1200.5	365.9	Interbedded mudstone , siltstone and sandstone
1120.5	341.5	Carbonaceous mudstone
1110.5	338.5	Sandstone

1107.5 337.5
Mudstone

1104.5 336.6
Slightly carbonaceous, cross-bedded, medium-grained lithic sandstone

1095.5 333.9
Mudstone

1081.5 329.6
Coal, #11 seam

1077.5 328.4
Carbonaceous shale

1076.5 328.1
Silty mudstone with some siltstone bands

1062.5 323.8
Medium-grained, lithic, poorly indurated, ridge-forming sandstone with large, oval, reddish-brown, limonite stains on weathered surfaces

980.5 298.8
Shale with clay ironstone nodules, #10 coal seam is covered but should lie between 950 and 980 ft (289.5 and 298.7 m)

965.5 294.3
Interbedded fine- to medium-grained recessive sandstone, siltstone and some carbonaceous shale

949.5 289.4
Very fine-grained sandstone

947.5 288.8
Very fossiliferous, orange-brown weathering siltstone

943.5 287.6
Mudstone with siltstone bands

939.5 286.3
Siltstone with some sandy bands

925.5 282.1
Shale

917.5 279.6
Flaggy, medium-grained, cross-bedded, slightly carbonaceous sandstone with some reddish-brown weathering clay ironstone nodules

899.5	274.2	Shale with some sandy and silty bands
876.5	267.1	Coal and coaly shale
871.5	265.6	Medium-grained argillaceous sandstone
869.5	265	Interbedded shale and siltstone
840.5	256.2	#8 seam
835.5	254.6	Shale with some fine- to medium-grained sandy zones at top and bottom
812.5	247.6	Carbonaceous and coaly shale
807.5	246.1	Siltstone with abundant plant fossils
802.5	244.6	Carbonaceous shale
791.5	241.2	Coal
786.5	239.7	Fine-grained silty sandstone with abundant plant fossils
761.5	232.1	Mudstone
756.5	230.6	Fine-grained silty sandstone
741.5	226	Mudstone with some coal from 727 to 729 ft (221.6 to 222.2 m)
709.5	216.2	Coal and coaly shale
706.5	215.3	Light grey weathering, blocky siltstone
698.5	212.9	Ridge-forming, massive, fine-grained, silty

sandstone, locally referred to as the 'Super 4 Sandstone'

638.5 194.6
Mudstone, massive near top, bedded near base

629.5 191.9
Coal, #4 seam

618 188.4
Fine-grained, argillaceous sandstone; silty in the upper 2 ft (0.6 m)

607 185
Mudstone with silty bands

599 182.6
Fine-grained sandstone

585 178.3
Mudstone, silty in the upper 10 ft (3 m); contains the 'Clam Zone'

550 167.6
Coal, #3 seam

545 166.1
Medium-grained lithic sandstone which weathers a light grey with some reddish-brown limonite staining

487 148.4
Interbedded mudstone, laminated siltstone and thinly bedded fine-grained sandstone

459 139.9
Chert pebble conglomerate with medium-grained sandstone matrix

458 139.6
Mudstone and siltstone with sandstone bands 0.5 to 1.5 ft (0.2 to 0.5 m) thick

421 128.3
Fine-grained sandstone with silty and shaly bands

Unit B

401 122.2
Mudstone with rare, orange-brown weathering, nodular ironstone bands and rare thin bedded and

cross-bedded fine-grained sandstone bands

Unit A

299.5 91.3
Carbonaceous, argillaceous and sandy laminated siltstone with abundant chert pebbles

295.5 90.1
Partially covered fine-grained sandstone, carbonaceous near the base

275.5 84
Carbonaceous siltstone and shale

271.5 82.7
Fine-grained argillaceous sandstone

262.5 80
Interbedded shale, siltstone and laminated siltstone with some cross-bedded, fine-grained sandstone bands

245.5 74.8
Covered

219.5 66.9
Massive fine-grained sandstone with rare bands of medium- and coarse-grained sandstone and some lenticular and cross-bedded zones

198.5 60.5
Mudstone becoming silty and sandy near the top

190.5 58.1
Thin bedded, fine-grained, carbonaceous sandstone which grades into silty sandstone near the top

176.5 53.8
Slightly sandy siltstone with abundant plant fossils

168.5 51.4
Coarse- and medium-grained sandstone with some interbedded fine-grained sandstone in the upper half, pebbly near the base

148.5 45.3
Chert pebble conglomerate with medium- and coarse grained sandstone matrix

146.5	44.7	Silty shale
144	43.9	Fine-grained argillaceous sandstone
142.5	43.4	Hard, carbonaceous mudstone with abundant plant fossils
137.5	41.9	Thin bedded, fine-grained sandstone and siltstone
132.5	40.4	Shale
129.5	39.5	Coal
128	39	Shale
126	38.4	Reddish-brown weathering siltstone
124	37.8	Covered, appears to be mainly shale but there may be a thin coal seam present
119	36.3	Medium grey weathering, fine- to medium-grained argillaceous sandstone
114	34.7	Medium-grained, brownish weathering, cross-bedded, flaggy sandstone
107	32.6	Partially covered, nodular, reddish-brown weathering mudstone
101	30.8	Coarse-and medium-grained sandstone
85	25.9	Coarse- to medium-grained, pebbly sandstone with common lenticular pebble conglomerate beds
70	21.3	Coal, #1 seam
66	20.1	Interbedded shale and fine-grained sandstone with

rare medium-grained sandstone bands

58.5 17.8
Nodular, silty, reddish-brown weathering mudstone

57.5 17.5
Shale with some thin fine-grained sandstone bands, plant remains and carbonaceous and coaly zones

47.5 14.5
Silty mudstone with abundant fossil plants

45.5 13.9
Fine-grained, silty sandstone

44.5 13.6
Carbonaceous shale with numerous plant fossils

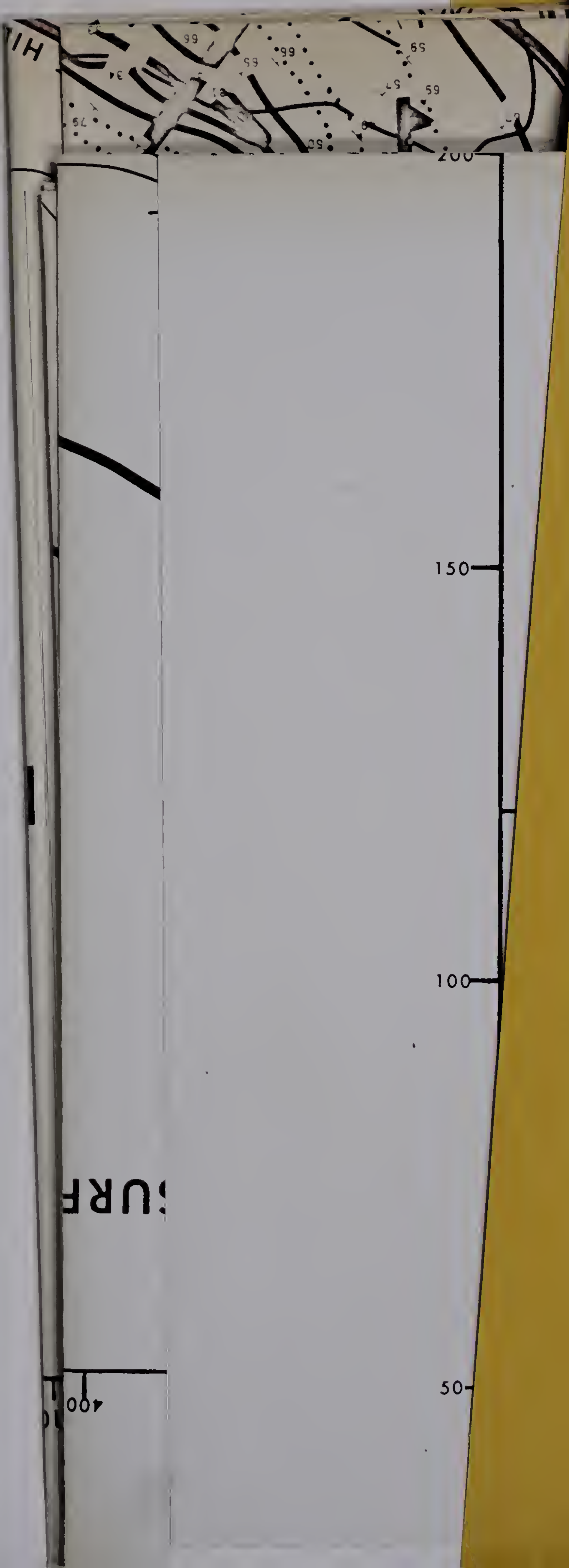
31.5 9.6
Fine-grained, silty sandstone

29 8.8
Carbonaceous shale with abundant plant remains

27 8.2
Reddish-brown weathering siltstone with some clay ironstone nodules

26 7.9
Interbedded siltstone and silty sandstone with some fossil plant remains

0 0
Cadomin Formation



200
150
100
50


GEOLOGY
OF THE
GRANDE CACHE AREA
N
1000 METRES
×100 FEET
220
280
350
410
470
290
240
170
FORMATION BOUNDARY
COAL SEAM
THRUST FAULT
ANTICLINE
ANTICLINE FLEXURE
SYNCLINE
SYNCLINE FLEXURE
OVERTURNED ANTICLINE
OVERTURNED SYNCLINE
BEDDING ORIENTATION
OVERTURNED BEDDING
ROAD-2 WHEEL DRIVE
ROAD-4 WHEEL DRIVE
Kk KASKAPAU
Kd DUNVEGAN
Ks SHAFTESBURY
Kld LUSCAR UNIT D
Klc LUSCAR UNIT C
Klb LUSCAR UNIT B
Kla LUSCAR UNIT A
Kcd CADOMIN
Jkn NIKANASSIN
TWO CAMP ANTICLINE
TWO CAMP CREEK
FOX CREEK
SYNCLINE
MOUNT HAMELL
PACKRAT CREEK
STERNE CREEK ANTICLINE
HELLS CREEK
COWLICK THRUST
SMOKY RIVER
SYNCLINE HILLS SYNCLINE
SYNCLINE HILLS THRUST
GRANDE MOUNTAIN
6520'
A
A'
B
B'
C
C'
D
D'
E
E'

FIGURE 4

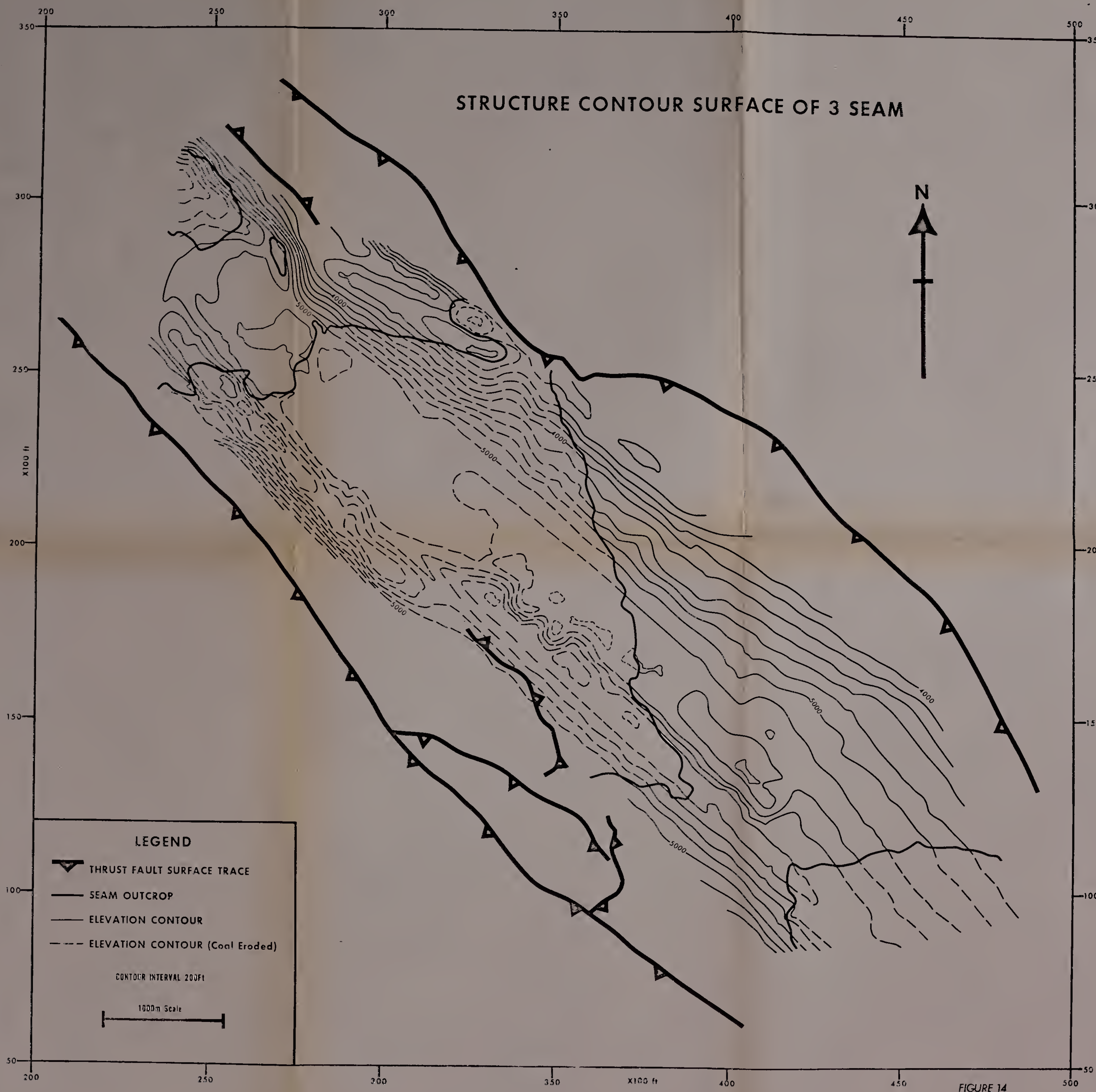

STRUCTURE CONTOUR SURFACE OF 3 SEAM
N
LEGEND
THRUST FAULT SURFACE TRACE
SEAM OUTCROP
ELEVATION CONTOUR
ELEVATION CONTOUR (Coal Eroded)
CONTOUR INTERVAL 200Ft
1000m Scale
X100 ft
X100 ft
200
250
300
350
400
450
500
50
100
150
200
250
300
350
5000
4000

FIGURE 14


OVERBURDEN THICKNESS ON 3 SEAM
N
LEGEND
THRUST FAULT SURFACE TRACE
OVERBURDEN CONTOUR
CONTOUR INTERVAL 200 FT
1000m Scale
1000
X100 ft
X100ft
200
250
300
350
400
450
500
50
100
150

FIGURE 15

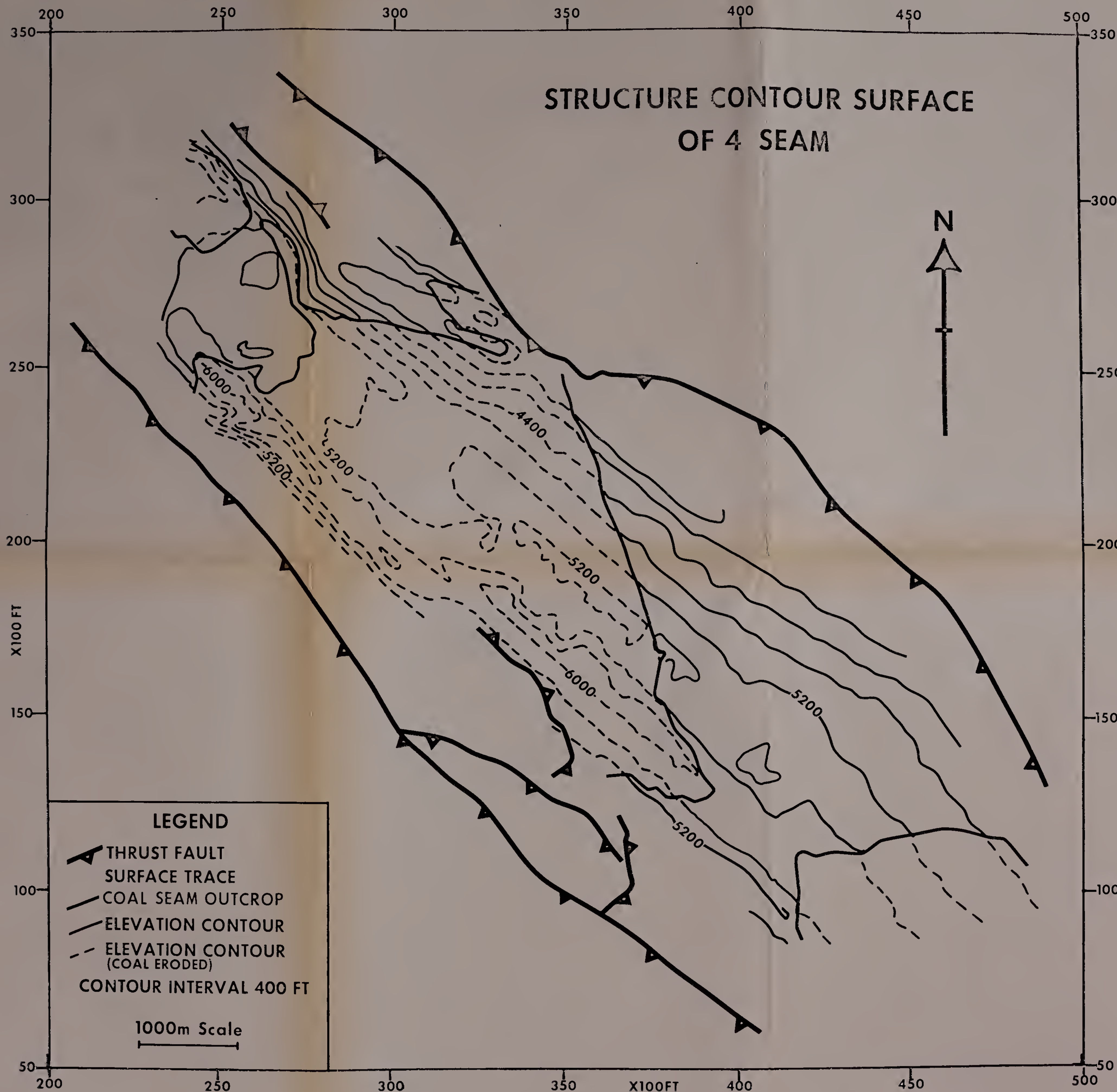

STRUCTURE CONTOUR SURFACE
OF 4 SEAM
N
LEGEND
THRUST FAULT
SURFACE TRACE
COAL SEAM OUTCROP
ELEVATION CONTOUR
ELEVATION CONTOUR
(COAL ERODED)
CONTOUR INTERVAL 400 FT
1000m Scale
X100 FT
X100FT
200
250
300
350
400
450
500
50
100
150
200
250
300
350
4400
5200
6000

FIGURE 16

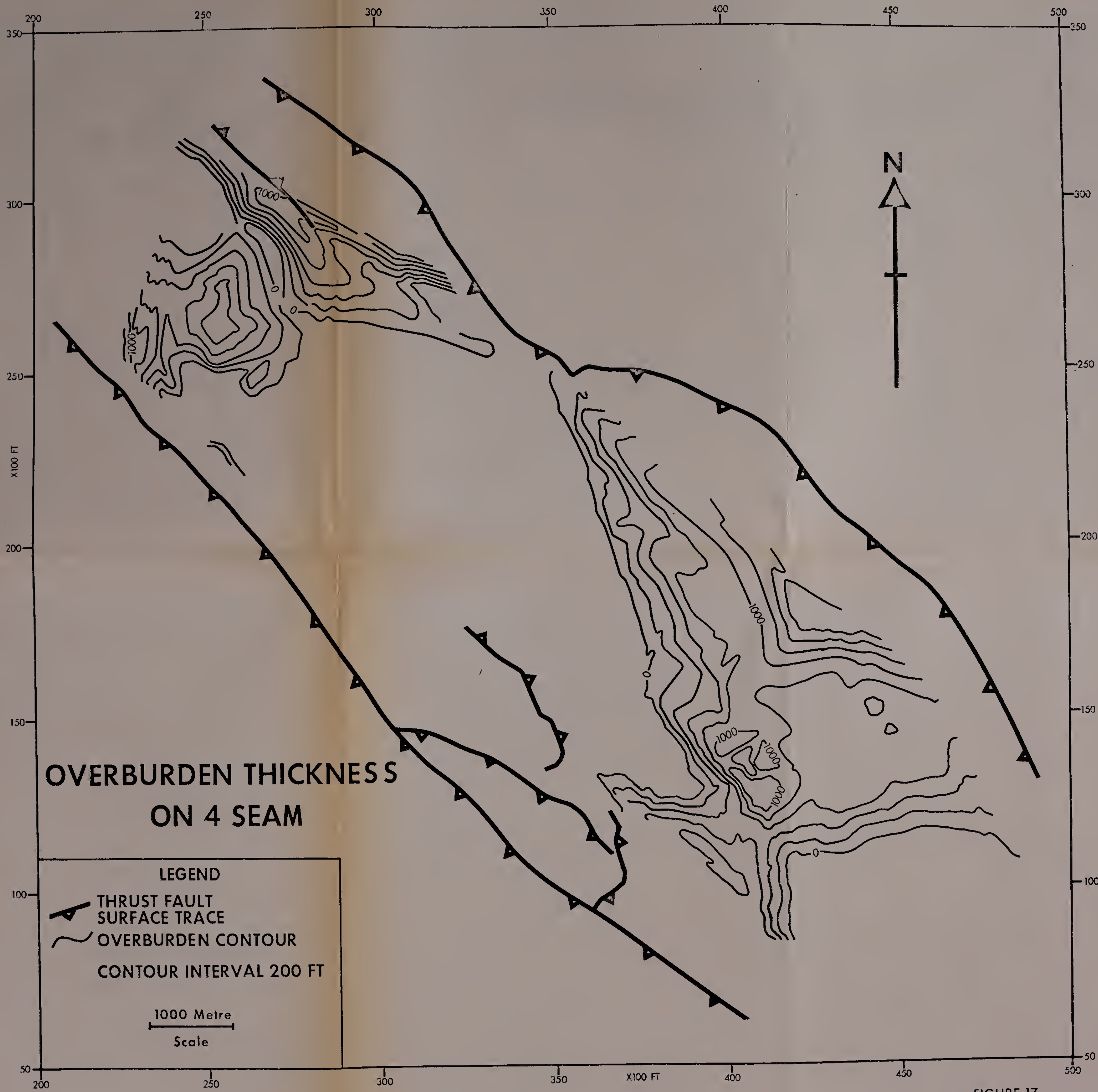

OVERBURDEN THICKNESS
ON 4 SEAM
LEGEND
THRUST FAULT
SURFACE TRACE
OVERBURDEN CONTOUR
CONTOUR INTERVAL 200 FT
1000 Metre
Scale
N
X100 FT
1000
0

FIGURE 17

STRUCTURE CONTOUR SURFACE OF 10 SEAM

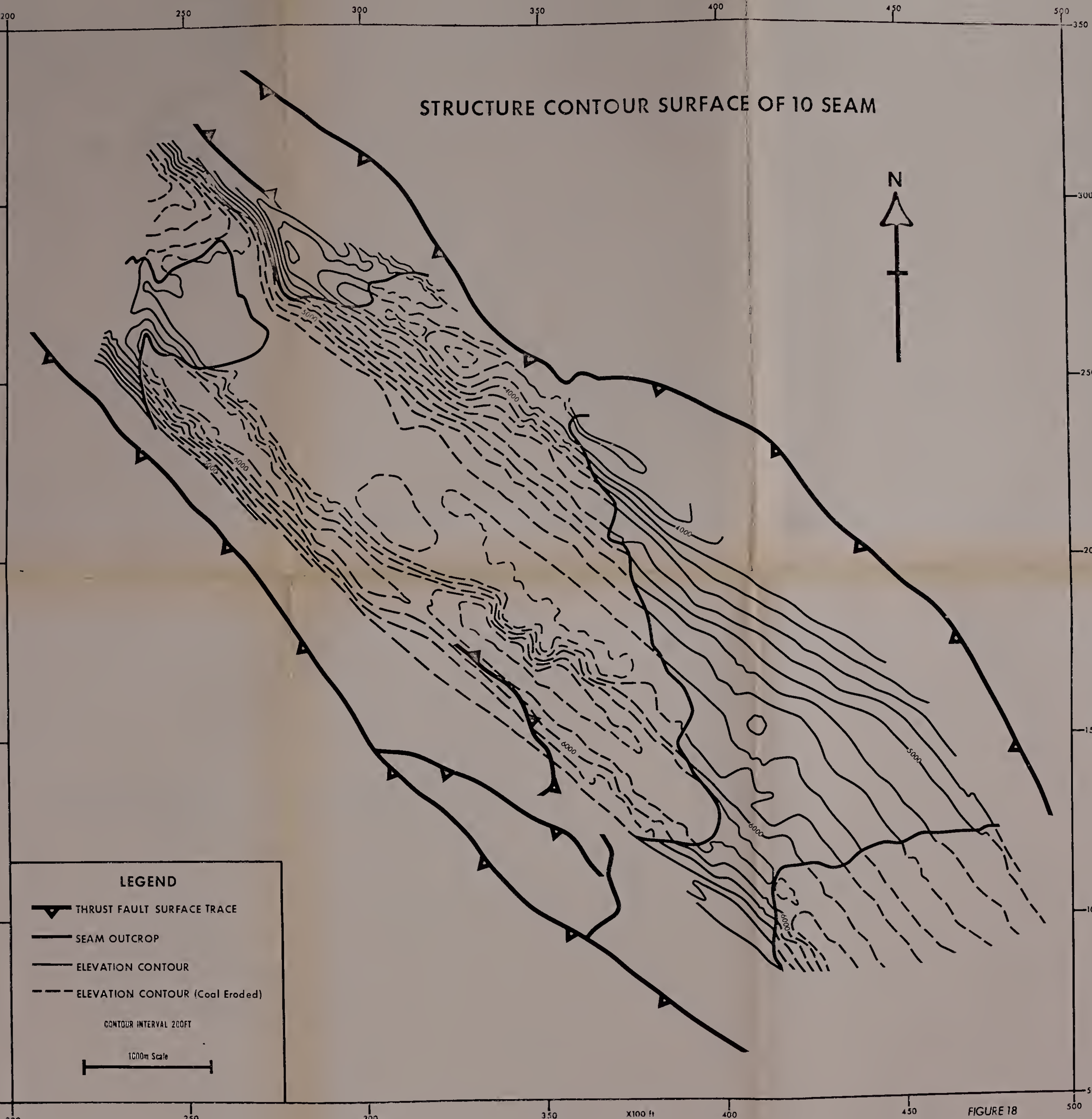
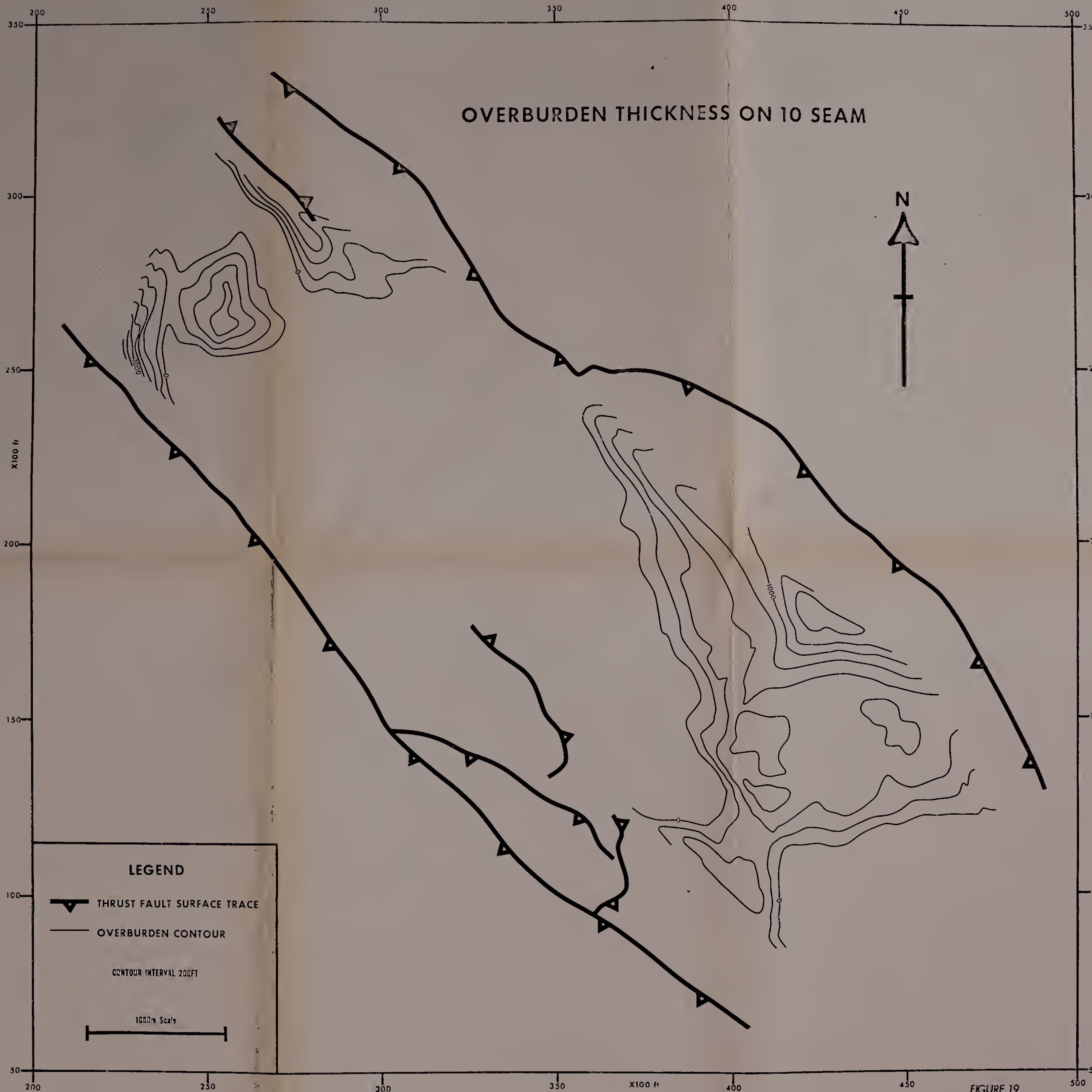


FIGURE 18



OVERBURDEN THICKNESS ON 10 SEAM
N
LEGEND
THRUST FAULT SURFACE TRACE
OVERBURDEN CONTOUR
CONTOUR INTERVAL 200FT
1000m Scale
X100 ft
1000
200
250
300
350
400
450
500
50
100
150

FIGURE 19